HYDROGEOLOGIC STUDY

OF

FRESHWATER AQUIFER

AND

DEEP GEOLOGIC FORMATIONS

SARNIA, ONTARIO

VOLUME I

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HYDROGEOLOGIC STUDY OF

THE FRESHWATER AQUIFER AND DEEP GEOLOGIC FORMATIONS

SARNIA, ONTARIO

VOLUME I

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EXECUTIVE SUMMARY

This report, in two volumes, describes the results of a hydrogeologic study of the Fresh Water Aquifer and deep geologic formations in the Sarnia, Ontario area. The study was undertaken to assess the extent to which the St. Clair River and a thin sand and gravel aquifer (Fresh Water Aquifer), located at the bedrock surface, have been impacted by past practices of industrial waste disposal to the Detroit River Group of Formations located at 150 to 200 m below bedrock surface.

To fulfill these objectives, reviews of existing information, completion of extensive field drilling, testing and sampling programs and computer modeling of the Fresh Water Aquifer and deep geologic formations were undertaken. The field programs completed in this study included: drilling, testing and installation of fifteen groundwater monitoring wells to the Fresh Water Aquifer; drilling, testing and installation of one 300 m deep borehole to the disposal formation in the Detroit River Group of Formations; and quarterly groundwater sampling and hydraulic head monitoring of a 29 point monitoring well network of the Fresh Water Aquifer and of the deep borehole. The computer modeling included a numerical simulation of groundwater flow in the Fresh Water Aquifer and simulation of waste migration within the disposal zone. The potential size of contaminant plumes that may result from vertical migration through an open abandoned borehole between the disposal zone and the Fresh Water Aquifer was also simulated using a computer model.

The results of this study show that the Fresh Water Aquifer is a thin, discontinuous aquifer located at or near the bedrock surface with an average hydraulic conductivity of 5×10^{-6} m/s. A buried bedrock valley of depth 60-80 m below ground surface and 30-40 m below surrounding bedrock is located about 500-1000 m east of the current channel of the St. Clair River. The Fresh Water Aquifer has a higher hydraulic conductivity of about 1×10^{-4} m/s within the bedrock valley due to the presence of alluvial sands and silts. The Fresh Water Aquifer is generally overlain by 30-70 m of low permeability clay till, however, below the St. Clair River the thickness of confining till in places may be a thin as 3 m.

Groundwater flow within the Fresh Water Aquifer toward the bedrock valley averages 0.57 m^3/a per unit aquifer width. Within the bedrock valley some flow is directed down to deeper geologic formations and some of the flow is discharged to the St. Clair River. No groundwater flows under the St. Clair River within the Fresh Water Aquifer to the U.S.

Phenol contamination of the Fresh Water Aquifer by injected industrial waste is evident on the Esso Petroleum Canada property near the St. Clair River and below the St. Clair River in the area of the CN railway tunnel. Loading to the St. Clair River from this 800 m by 600 m contaminated zone is calculated at 5.2 g/d which, given the volume of flow in the St. Clair River, is rapidly reduced to below detection levels. Chloride contaminant loading to the River from the same area is calculated at 50 kg/d. Cleanup of this contaminated zone by groundwater pumping is potentially dangerous and may introduce more contamination to the fresh water aquifer.

It is recognized that some undetected contaminant plumes may exist in the vicinity of disposal wells due to waste migration up abandoned or poorly completed boreholes. Assuming such plumes did exist adjacent to the St. Clair River the total potential phenol loading to the River is estimated at 25 g/d. This would result in an increase in phenol concentration in the River of 0.057 ng/L which is much less than the minimum detection limit of 1 ug/L. This potential phenol loading is small in comparison to other municipal/industrial point source loadings to the St. Clair River in the Sarnia area.

Industrial waste, characterized by phenol (30,000 - 40,000 ug/L), volatile organics (e.g., benzene, toluene, etc. - 200-5800 ug/L) and naphthalenes (50 - 829 ug/L) is restricted to a narrow 11 m zone of residual contamination between 185.9 and 196.6 m depth in the upper section of the Lucas dolomite. Vertical migration of this waste through the pore space of the overlying and underlying rocks has been negligible and measured hydraulic heads show fluid flow

in the adjacent rocks is now towards the zone of residual contamination. This study suggests that there is a relatively active flow system within the disposal formation today and that understanding the fate of the 8,000,000 m^3 of industrial waste disposed to the Detroit River Group will require knowledge of the current rates and directions of flow within the disposal zone.

The hydraulic head within the zone of residual contamination is now 14-15 m below that in the Fresh Water Aquifer and 8 m below the level of the St. Clair River. Therefore current potential flow directions are from the Fresh Water Aquifer and St. Clair River to the disposal zone.

The chemical composition of the industrial waste collected from the Lucas dolomite does not contain chlorinated volatile organics such as perchloroethylene and carbon tetrachloride and therefore is dissimilar to the St. Clair River "blobs" detected in 1985. This chemical dissimilarity and the hydraulic head relations described above indicate that the St. Clair River "blobs" were not related to upward movement of industrial waste from the Detroit River Group of Formations to the St. Clair River.

A significant finding of this study was the occurrence of high hydraulic conductivity limestone layers in the Hamilton Group of Formations at 74 and 123 m depth that likely contain industrial waste at phenol concentrations of 6000 - 10,000 ug/L and hydraulic heads due to gas pressure that are above those in the Fresh Water Aquifer. The 2 m thick limestone layer at 74 m depth is of particular concern to this study because groundwater from this horizon likely discharges to the Fresh Water Aquifer within the bedrock valley and this horizon flowed industrial waste in 1967 and 1969 at rates of 10 - 238 L/min. The extent of contamination in this and the 123 m depth horizon is not known but is likely significant as the only two monitoring wells in these horizons (from this and an earlier study) detected industrial waste. This waste was likely introduced to these limestone horizons from improperly completed disposal, cavern or abandoned wells.

Recommendations for further work are developed in this study to further define the hydrogeologic and contaminant migration potential of the Fresh Water Aquifer and deep geologic formations. Ongoing water level monitoring and groundwater quality sampling is recommended in the established Fresh Water Aquifer monitoring well network and the deep borehole to the disposal formation. Additional boreholes are recommended to the limestone units at 74 and 123 m depth to define the levels and extent of contamination and the groundwater flow rates and directions. Two additional boreholes to the disposal horizon in the Detroit River Group are recommended to aid in determining the fate of the 8,000,000 m^3 of injected industrial waste.

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1. INTRODUCTION

1.1 BACKGROUND

Pressurized injection of liquid industrial waste into deep geologic formations was a common disposal practice in Lambton County from about 1958 to 1974. Figure 1.1 shows the location of industrial waste, oil field brine and brine disposal wells in parts of Lambton County and the area of the current study. Over this period, approximately 8,000,000 cubic meters of industrial waste, consisting of waste acids, caustic fluids, phenolic waters and sulphides were injected into the Detroit River Group of Formations. The Detroit River Group of Formations are a sequence of porous and permeable dolomite and dolomitic limestone of Devonian age located, in the Sarnia area, at a depth of about 190 to 330 m below ground surface. A schematic of the Sarnia bedrock geology, formation thickness and a typical disposal well are shown in Figure 1.2. During the life of deep well disposal operations, several occurrences of breakouts (i.e., waste flow at surface) were reported within a distance of 3 to 4 km of the injection wells. In response to concern over potential contamination of a thin sand and gravel water supply aquifer located at the bedrock surface and of the St. Clair River by the discharge of injected wastes, the Ontario Ministry of the Environment (MOE), Environment Canada (EC) and Esso Petroleum Canada (EPC) initiated studies to investigate the aquifer. The aquifer is located beneath 35 to 70 m of clay and clay till and is identified in this and other studies as the Fresh Water Aquifer.

The MOE and EC studies of the Fresh Water Aquifer in the Sarnia area are structured into four work phases. Phase I studies provided an assessment of past deep well disposal practices and were completed by Underground Resources Management (URM, 1984) and Geologic Testing Consultants (GTC, 1985). Phase II studies included the installation of a monitoring well network and a sampling program for the Fresh Water Aquifer. An initial but limited monitoring well network and groundwater sampling program were established by MOE in 1985 (GTC, 1985; Fleming, 1986). Subsequent studies by Environment Canada in 1986 (INTERA, 1987a) expanded the monitoring well network and assessed the hydraulic properties

Legend:

■ — Industrial Waste Injection

★ — Cavern-Washing Brine Injection

● — Oil-Field Brine Injection

▲ — Oil-Field Brine Injection to Guelph Fm

LOCATION OF DISPOSAL WELLS AND
STUDY AREA IN LAMBTON COUNTY

FIGURE 1.1

Depth Below Surface (m)

Depth	Formation
0	SURFACE
	Glacial Deposits
40	
	KETTLE POINT FM
85	
	HAMILTON GROUP
165	DUNDEE FM
205	
	DETROIT RIVER GROUP
	LUCAS FM
277	AMHERSTBURG FM

Well components labeled: 17 1/2" Conductor Pipe; 10 3/4" Surface Casing; Corrosion Inhibiting Annulus Fluid; Cement to surface; 7" Longstring Casing; Packer; 3" Steel Tubing; 6 7/8" Open Hole

Drawn by	Date	SCHEMATIC OF A DISPOSAL WELL ILLUSTRATING THE BEDROCK GEOLOGY AND FORMATION THICKNESSES IN LAMBTON COUNTY (AFTER URM, 1984)
Checked by	Date	
Revisions	Date	
		FIGURE 1.2

of the Aquifer. Phase III studies were commissioned by MOE in June 1987 and included a comprehensive hydrogeologic study of the Fresh Water Aquifer and deep geologic formations in the Sarnia area. The results of Phase III studies are the subject of this report. Phase IV studies, if deemed necessary, based on the results of Phase III work would include continued hydrogeologic investigation of the Fresh Water Aquifer and the initiation of a detailed examination of the hydrogeology of the Detroit River Group of Formations.

1.2   STUDY OBJECTIVES

The overall objectives of Ontario Ministry of the Environment and Environment Canada studies of the Fresh Water Aquifer in the Sarnia area are to assess the extent to which the Fresh Water Aquifer and the St. Clair River are impacted by past practices of industrial waste disposal to the Detroit River Group of Formations. The objectives of the current Phase III studies are:

1)   Map the pattern of groundwater flow in the Fresh Water Aquifer and evaluate the magnitude and direction of hydraulic gradients in the vicinity of the St. Clair River by use of a computer model of groundwater flow;

2)   Indicate the extent to which the Fresh Water Aquifer may be contaminated by waste disposed in the Detroit River Group, or formation fluids displaced by the disposal of waste under pressure, or wastes from other sources, by correlation of corrected hydraulic heads in various bedrock units and aided by the specific analysis of groundwater for various contaminants;

3)   Compute the flux of contaminants to, and beneath the River by mathematically modeling the Fresh Water Aquifer and;

4)   Characterize the groundwater quality in the Detroit River Group and overlying formations.

1.3   STUDY SCOPE

To meet the study objectives, reviews of existing information, completion of extensive field drilling, testing and sampling programs and computer modeling of the Fresh Water Aquifer and deep geologic formations were undertaken. The field programs included:

1)   Drilling, testing, and installation of 15 groundwater monitoring wells to the Fresh Water Aquifer;

2)   Drilling, testing and installation of one 300 m deep, multi-level monitoring well to the disposal formation in the Detroit River Group of Formations;

3)   Groundwater sampling and hydraulic head monitoring of the complete MOE and EC monitoring well network of the Fresh Water Aquifer (total 29 wells) and the deep monitoring well on a quarterly basis for one year.

The computer modeling undertaken in this study included:

1)   a numerical simulation of groundwater flow in the Fresh Water Aquifer to the St. Clair River and,

2)   A simulation study of waste migration within the disposal formation and the potential size of contaminant plumes within the Fresh Water Aquifer that would result from vertical migration through an open abandoned borehole.

This report in two volumes describes the studies of the Fresh Water Aquifer and deep geologic formations. Volume I is the text of the report. The Appendices are included in Volume II. Section 2 of the report provides a review of the setting and previous studies in the Sarnia area including geologic setting, hydrogeologic setting, deep well disposal operations, and historical

occurrences of waste breakouts. Section 3 of the report describes the methodology, results and interpretations of studies of the Fresh Water Aquifer. Section 4 describes similar components of the studies of the deep geologic formations. Section 5 summarizes the methodology and results of the computer modeling of the Fresh Water Aquifer and deep geologic formations. The extent, potential migration and impact of contamination in the Fresh Water Aquifer and deep geologic formations are discussed in Section 6. Section 7 summarizes the conclusions and recommendations of this study.

2.   STUDY AREA SETTING AND PREVIOUS WORK

2.1   GEOLOGIC SETTING

The study area is located near the crest of a structural high of Precambrian rock known as the Algonquin Arch which separates two Paleozoic continental basins, the Michigan Basin to the northwest and the Allegheny Basin to the southeast. Associated with the Algonquin Arch is the Findlay Arch to the southwest and the Chatham Sag formed by the plunge of the two arches. The major geologic features of the Great Lakes area are shown in Figure 2.1 from Uyeno et al. (1982).

The Sarnia area is located on the eastern rim of the Michigan Basin and is underlain by sedimentary deposits of Cambrian, Ordovician, Silurian and Devonian age (Caley 1946; Sanford and Brady, 1955; Sanford, 1968; Winder and Sanford, 1972). The Paleozoic rocks in this area are either flat lying or dip gently to the northwest at a rate of 6-9 m/km and average 1350 m in thickness. Local variations in dip result from collapse structures associated with dissolution of deeper Silurian salt beds or sediment draping over reefal structures (Brigham, 1971). The stratigraphic succession and geologic plan for southwestern Ontario are shown in Figures 2.2 and 2.3.

Normal faulting of minor displacement intersecting rocks up to and including Devonian age is known to occur in southwestern Ontario. Where such faults traverse the Silurian salt beds there has been widespread leaching along the faults with consequent collapse of overlying strata which forms elongate depressions in the bedrock formations (Winder and Sanford, 1972). Sanford et al. (1985) suggests that such dissolution along rejuvenated vertical fractures is the basis for hydrocarbon accumulation in Middle Devonian rocks of southwestern Ontario and that such fractures form part of a regional fracture and fault block system for Paleozoic rocks of southwestern Ontario.

8

LEGEND

7 PERMIAN

6 PENNSYLVANIAN

5 MISSISSIPPIAN

4 DEVONIAN

3 SILURIAN

2 ORDOVICIAN

1 CAMBRIAN

PRECAMBRIAN

Major structural elements

Kilometres

0   100   200
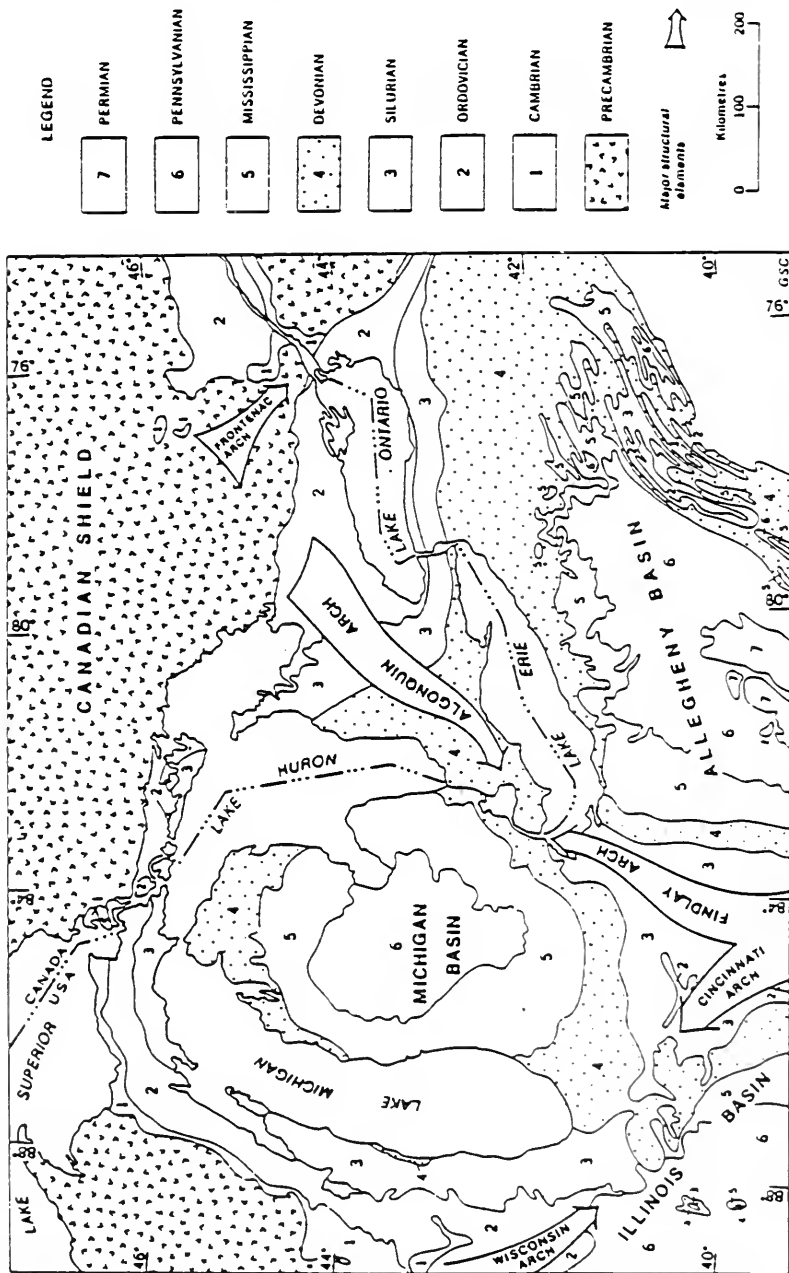
FIGURE 2.1

MAJOR GEOLOGIC FEATURES OF THE GREAT LAKES AREA
(AFTER UYENO ET AL., 1982)

ERA	SYSTEM	GROUP	FORMATION	PRIMARY LITHOLOGY	APPROX. DEPTH in LAMBTON CO. Ft. (m)
Ceno-zoic	Pleistocene		Glacial Till	Sand, Clay	0
Paleozoic	Devonian	Port Lambton		Shale	Missing at Well site
			Kettle Point	Shale	170 (52)
		Hamilton	Ipperwash	Limestone	220 (66)
			Widder	Shale and Limestone	
			Hungry Hollow	Limestone and Shale	
			Arkona	Shale	
			Bartlett Quarry	Limestone	
			Bell	Shale	
			Marcellus	Shale w/Limestone	
			Dundee ●☼	Limestone	460 (177)
		Detroit River	Lucas ●	Dolomite	715 (216)
			Amherstburg	Limestone and Dolomite	860 (260)
			Bois Blanc	Dolomite and Limestone	1115 (340)
			Oriskany	Sandstone	
	Silurian		Bass Islands	Dolomite	1160 (390)
			Salina ●☼	Halite, Anhydrite, Limestone, Dolomite, Shale	1330 (406)
			Guelph-Lockport ●☼	Dolomite	2510 (766)
		Amabel	Goat Island ☼	Dolomite	2540 (774)
		Cataract	Grimsby ●☼	Sandstone	2625 (800)
			Cabot Head	Shale	
			Manitoulin	Dolomite	
			Whirlpool ●☼	Sandstone	
	Ordovician			Shale	2630 (460)
			Meaford-Dundas	Shale	
			Blue Mountain	Shale	
			Collingwood	Shale	
		Trenton	Cobourg ☼	Limestone	3440 (1044)
			Sherman Fall ●☼	Limestone and Shale	
			Kirkfield	Limestone	
		Black River	Coboconk ☼	Limestone	2626 (1146)
			Gull River ☼	Limestone	
			Shadow Lake	Shale	
	Cambrian		Trempealeau	Dolomite	4460 (1366)
			Eau Claire ●☼	Dolomite and Sandstone	
			Mount Simon	Sandstone	
	Precambrian			Igneous Rocks	4620 (1378)

Depths from electric log of Imperial Moore No. 48 R.F. Moore Township
Adapted from Geol. Surv. Canada, 1983, Watson, 1966, and Sanford and Quillett, 1983

● Oil   ☼ Gas

Drawn by	Date	STRATIGRAPHIC SUCCESSION IN LAMBTON COUNTY (AFTER URM, 1984)
Checked by	Date	
Revisions	Date	

FIGURE 2.2

LEGEND

PALEOZOIC

UPPER DEVONIAN
20 — PORT LAMBTON FORMATION
Gray shale and sandstone
19 — KETTLE POINT FORMATION
Black shale

MIDDLE DEVONIAN
18 — HAMILTON FORMATION
Gray shale and sandstone
17 — DUNDEE FORMATION
Limestone
16 — DETROIT RIVER GROUP
Limestone and dolomite
15 — BOIS BLANC FORMATION
Cherty limestone

LOWER DEVONIAN
14 — ORISKANY FORMATION
Sandstone

SILURIAN
13 — BASS ISLANDS (BERTIE) FORMATION
Dolomite
12 — SALINA FORMATION
Dolomite, shale, gypsum, salt

MIDDLE AND LOWER SILURIAN
11 — GUELPH FORMATION
Dolomite
10 — LOCKPORT - AMABEL FORMATIONS
Dolomite
9 — CLINTON AND CATARACT GROUPS
Sandstone, shale, dolomite[a]

ORDOVICIAN
UPPER ORDOVICIAN
8 — QUEENSTON FORMATION
Red shale
7 — GEORGIAN BAY (CARLSBAD AND HUSSELL) FORMATION
Gray shale with limestone interbeds, limestone upper member on Manitoulin Island
6 — WHITBY (EASTVIEW AND BILLINGS[b] FORMATION
Gray and black shale

MIDDLE ORDOVICIAN
5 — SIMCOE GROUP (TRENTON-BLACK RIVER)
Limestone
4 — CHAZY GROUP
Limestone and shale

LOWER ORDOVICIAN
3 — BEEKMANTOWN GROUP
Dolomite, sandstone

CAMBRO-ORDOVICIAN
2 — POTSDAM OR NEPEAN FORMATION
Sandstone

PRECAMBRIAN
1 — Precambrian rocks

SOURCES OF INFORMATION
a Dolomite predominates on Manitoulin Island
b Formations in Ottawa area

Compilation by B A Liberty and D F Hewitt, 1972
Geology from maps of the Geological Survey of Canada

GEOLOGY OF SOUTHWESTERN ONTARIO
(AFTER HEWITT AND FREEMAN, 1972)

FIGURE 2.3

Because industrial waste disposal was to the Detroit River Group of Formations, and potentially impacted resources include the Fresh Water Aquifer and the St. Clair River, the geologic formations of interest in this study include those of the Detroit River Group and overlying formations. Brief descriptions of the underlying formations to the Salina formation are also provided in this report for completeness and because the Salina Formations are utilized for pressurized product storage in the Sarnia area. The Salina Formation consisting of halite, anhydrite, limestone, dolomite and shale is assumed, for the purpose of the present study to be of low hydraulic conductivity and therefore a barrier to vertical groundwater flow. Descriptions of each formation in the Sarnia area are provided below in descending order.

2.1.1   Overburden

The Sarnia area is underlain by approximately 30 - 70 m of glacial drift consisting of fine-grained glacial tills and a thin (1 - 3 m thick) discontinuous sand and gravel layer (Fresh Water Aquifer) generally located at the top of rock. These thick clay deposits around Sarnia form part of the St. Clair Clay Plain (Chapman and Putnam, 1966) and their geology, mineralogy and soil properties are described by Soderman et al. (1961), Dreimanis (1961), Quigley and Ogunbadejo (1976), Fitzgerald et al. (1979) and others. The near surface properties of these tills have also been extensively studied because of the location of several municipal and industrial waste landfills in the Sarnia area (Goodal and Quigley, 1977; Crooks and Quigley, 1984; Johnson et al., 1986; Richards et al., 1984; D'Astous et al., 1988).

The clay tills in the Sarnia area are believed to be of late Wisconsin age and derived from reworking of previous unconsolidated alluvial deposits and underlying limestones and shales. Except for a fractured, very stiff, desiccated crust extending to about 7 m depth, the tills are fairly homogeneous although some distinction of tills has been made above 27 m depth (Quigley and Ogunbadejo, 1976). The tills contain 40 - 50% clay, 10% sand and the remainder as silt.

The basal, thin, discontinuous sand and gravel layer of the Fresh Water Aquifer is described from monitoring well studies by GTC (1985), Gartner-Lee Associates Limited/Esso Petroleum Canada (GLAL/Esso, 1987) and INTERA (1987a).

The thickness of overburden in the Sarnia area is determined principally by the topography of the bedrock surface which until recently was assumed to be flat lying at a depth of 30 - 40 m (Fitzgerald, 1979) and average elevation of 150 m above mean sea level (AMSL). Recent work by GLAL/Esso (1987) and INTERA (1987a) have identified a 30 - 35 m deep bedrock valley located immediately east of the St. Clair River and subparalleling the River from Sarnia in the north to as far south as Mooretown south of Stag Island. GLAL/Esso (1987) reported that the bedrock valley is filled with about 17 m of silts, silty sands and sands which are likely of fluvial or glacial outwash origin. Additional descriptions of the bedrock valley including the results of the current study are given in Section 3.2.2.

Below the St. Clair River, the bedrock surface is relatively flat (elevation 146-150 m AMSL) in the vicinity of the CN tunnel (Engineering News, 1890) and the Sarnia - Port Huron (Blue Water) Bridge (Michigan State Department of Transportation, 1937). The overburden in these areas consists of alluvial sands and gravels overlying clay till. Figure 2.4 shows the CN tunnel and the results of geotechnical borings completed in 1885 and 1888. Of particular interest in this figure is the thickness of alluvial sands and gravels near the Canadian side on a centre line of borings made 15 m (50 ft) south of the current tunnel. Sands and gravels in this location extend to the elevation of the top of the tunnel (160 m AMSL). Geotechnical borings completed in 1937 for the Blue Water bridge also indicate sands, gravels, and silts to elevations of 153 m AMSL on both sides of the St. Clair River. These borings in conjunction with observations of significant sand and gravel inflows during earlier CN tunnel construction attempts and gas blow outs to the St. Clair River during the successful tunnelling effort (Patton, 1897) suggest the sands and gravels, particularly on the Canadian side, extend to the tunnel elevation and that the thickness of clay till in this location may be as thin as 3 m.

PROFILE OF PART OF ST. CLAIR TUNNEL UNDER RIVER SHOWING SECTION OF RIVER BED AS DETERMINED BY BORINGS.
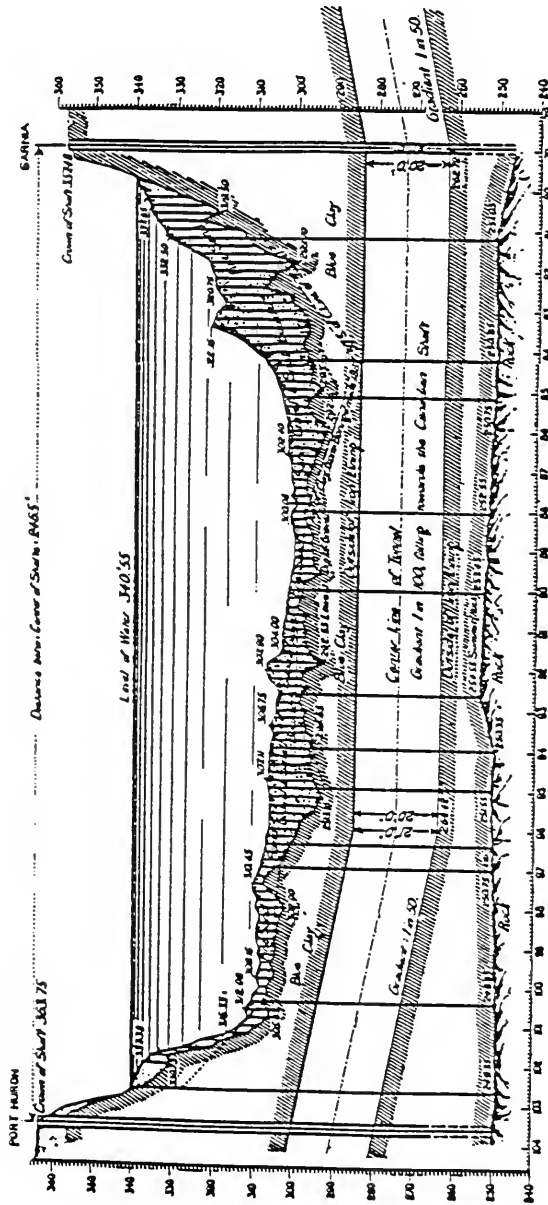
CN ST. CLAIR RIVER TUNNEL (AFTER ENGINEERING NEWS, 1890)

FIGURE 2.4

Overburden conditions on the U.S. side of the St. Clair River opposite Sarnia in St. Clair County are described by Western Michigan University (1981) and Erdmann (1987) and are generally similar to Canadian conditions. Rural drinking water supply is obtained from a thin layer of granular material and the upper, fractured bedrock (also termed Fresh Water Aquifer) which are confined by a thick till layer.

2.1.2   Kettle Point Formation

The Kettle Point Formation of the Port Lambton Group is a black bituminous shale that forms the bedrock beneath most of the study area and Lambton County. This Upper Devonian formation is generally flat-lying, with greenish grey silty shale layers and averages 15 m thickness in the Sarnia area. The formation attains a maximum thickness of 60 - 90 m in eastern Michigan. In the study area and in St. Clair County, Michigan the upper 1-2 m of the Kettle Point Formation is fractured and weathered and forms part of the Fresh Water Aquifer. Winder and Sanford (1972) report northwest-southeast and north-south striking fractures within outcrops of the Kettle Point shale.

Because the bedrock valley extends to depths of 70 m below ground surface, the Kettle Point shales are absent in the deepest parts of the bedrock valley. Limestones and shales of the Hamilton Group form the bedrock surface in these locations.

The Kettle Point organic shales are easily identified on natural gamma geophysical logs as very high gamma response (Beards, 1967) (>300 counts/sec) likely due to the presence of uranium precipitated by organic material (Johnson et al., 1983).

2.1.3   Hamilton Group of Formations

Underlying the Kettle Point shales and overlying the Dundee limestone are a thick sequence of Devonian age interbedded shale and limestone formations known as the Hamilton Group of Formations. In southwestern Ontario, the Hamilton

Group comprises the following formations (in descending order): Ipperwash, Widder, Hungry Hollow, Arkona, Rockport Quarry, and Bell Formation (Figures 2.2 and 2.3). The Hamilton Group of Formations average 90 m thickness in the Sarnia area and are an important group in this study because they are considered the main confining unit between the Detroit River Group disposal zone and the Fresh Water Aquifer. In the bedrock valley, the Hamilton Group of Formations are in direct contact with the Fresh Water Aquifer. The following paragraphs describe the geology of the Hamilton Group of Formations in descending order.

2.1.3.1   Ipperwash Formation. The Ipperwash Formation averages 2-13 m thickness in southwestern Ontario (Uyeno et al., 1982) which is due in part to the erosional discontinuity between it and the overlying Kettle Point Formation. The formation consists of medium to coarse grained, grey brown, bioclastic limestone. Large holes of up to 0.15 m diameter and several metres length have been observed in surface exposures of the Ipperwash.

2.1.3.2   Widder Formation. The Widder Formation is reported by Winder and Sanford (1972) as averaging 14-16 m thickness in southern Ontario and consists of a variety of lithologies with soft, grey, calcareous shale interbedded with blue-grey, fine- grained argillaceous limestone, coarse-grained crinoidal bioclastic limestone and several beds of nodular limestone (Uyeno et al., 1982). Shale comprises over 50% of the unit. In conjunction with the underlying Hungry Hollow Formation, the Widder has been termed the "middle limestone" in many older well logs of the Sarnia area. Limestone sections of the Widder Formation form the bedrock in the deeper sections of the bedrock valley. GLAL/Esso (1987) report based on geophysical logs that several limestone horizons in the Widder Formation show good correlation between Esso Petroleum Canada (EPC) disposal wells DW-2, DW-3, and DW-5.

2.1.3.3   Hungry Hollow Formation.   The Hungry Hollow Formation is a thin (1-2 m thickness) coarse grained crinoidal bioclastic limestone which is persistent and maintains a uniform thickness throughout the Sarnia area. It is considered a marker horizon and is easily recognized on neutron activation and natural gamma logs (Beards, 1967) in oil and gas wells. The Hungry Hollow

Formation is identifiable on EPC geophysical logs (GLAL/Esso, 1987) for disposal wells DW-2, DW-3, DW-5 at depths of 85-88 m.

2.1.3.4 Arkona Formation. Underlying the Hungry Hollow Formation is a thick blue-grey clay shale with occasional thin discontinuous limestone lenses known as the Arkona Formation. Average thickness of this unit is 35 m in the Sarnia area, and in conjunction with the Rockport Quarry and Bell Formations, this unit is known locally on older well logs as the Lower Shale.

2.1.3.5 Rockport Quarry Formation. The Rockport Quarry Formation is a grey and brown, very fine-grained limestone with occasional thin shale layers (Uyeno et al., 1982). Sanford (1968) indicates the unit is only about 6 m thick in southwestern Ontario and geophysical logs of the EPC disposal wells DW-2, DW-3 and DW-5 show the formation with thickness of 2-6 m. This formation is also readily identifiable on geophysical logs because of the contrast in rock properties of the limestone between the overlying Arkona shale and underlying Bell Shale.

2.1.3.6 Bell Formation. Underlying the Rockport Quarry Formation and disconformably overlying the Dundee Formation is a 15-18 m thick, soft, blue and grey calcareous clay shale known as the Bell Formation. Limestone lenses often occur in the lower part of the unit and EPC (GLAL/Esso, 1987) geophysical logs indicate the formation in the vicinity of disposal wells DW-2, DW-3 and DW-5 averages 18 m thickness.

2.1.4   Dundee Formation

Underlying the Hamilton Group and disconformably overlying the Detroit River Group is the Dundee Formation. The formation consists of medium to thick bedded, dark brown fossiliferous micritic limestone. The upper contact with the Bell shale is readily identifiable in core logs and geophysical logs and in the Sarnia area occurs at a depth of about 145 m. The formation averages 40 m thick-

ness in the Sarnia area based on EPC disposal well logs and other well log data (GLAL/Esso, 1987) and includes bituminous laminations, shale partings and coarse-grained, crinoidal bioclastic limestone sections. The lower sections of the formations are reported as sandy.

Occurrences of both oil and gas have been reported in the Dundee Formation in southwestern Ontario. Many thousands of exploratory holes were drilled in Lambton County in the late 1800's and early 1900's in search of oil and gas in the Dundee Formation (URM, 1984; McLean, 1968) and the drilling and plugging records of most of the wells are not known.

2.1.5   Detroit River Group of Formations

The Detroit River Group of Formations consist of limestone and dolomite of the Lucas Formation and underlying Amherstburg Formation. The Lucas Formation was the principal disposal formation for liquid industrial waste in the Sarnia area.   The Detroit River Group of Formations average 140 m thickness in the Sarnia area (GLAL/Esso, 1987; Vandenberg et al., 1977; McLean, 1968).

2.1.5.1   Lucas Formation.   The Lucas Formation averages 80 - 90 m thickness in northern Lambton County (McLean, 1968) and this thickness appears representative for the Sarnia area based on compilation of well log data (Vandenberg et al., 1977; GLAL/Esso, 1987). This compilation also indicates the top of the formation dips gently to the southwest.

The Lucas Formation consists of a variety of lithologies but principally micro-crystalline dolomites with halite and anhydrite layers (Winder and Sanford, 1972).   The occurrence of anhydrite and halite in the formation increases toward the centre of the Michigan Basin. Dissolution of anhydrite layers in the upper sections of the Lucas Formation are thought to be the cause of the high porosity zones utilized for industrial waste injection.   Lost circulation zones are reported for the Lucas Formation east of Sarnia (URM, 1974), but no lost circulation zones were encountered during drilling of the ESSO disposal wells and these wells were acid treated and hydraulically fractured to increase injection rates (GLAL/Esso 1987). The middle and lower sections of the Lucas contain less anhydrite and are more finely crystalline with dark bituminous

laminations (Uyeno et al., 1982). Sections of the Lucas Formation are also oil bearing (URM, 1984).

2.1.5.2 Amherstburg Formation. The Amherstburg Formation is a succession of dolomites and limestones of Middle Devonian age underlying the Lucas Formation. Both the overlying contact with the Lucas Formation and underlying contact with the Bois Blanc Formations are not clearly defined. The unit averages 60 m thickness in the Sarnia area, is sucrosic in sections on the rim of Michigan Basin (Winder and Sanford, 1972) and contains bituminous laminations and chert nodules.

2.1.6   Bois Blanc Formation

The Bois Blanc Formation consists of interbedded limestones and dolomites. The formation thickness varies from 40 - 60 m in Lambton County with thicker sequences overlying dissolution zones in the Salina salt beds. A basal sandy facies of up to 3 m thickness is reported for the formation in southwestern Ontario by Sanford (1968) and this sandy unit in other locations is known as the Oriskany sandstone.

2.1.7   Bass Islands Formation

The Bass Island Formation of Upper Silurian age consists of tan and brown sucrosic to micro-crystalline dolomites which in Lambton County average 110 m thickness. The formation conformably overlies the Salina and the beds are commonly platy to laminated.

2.1.8   Salina Formation

The Salina Formation is a thick (400 m average thickness) sequence of Upper Silurian halite, anhydrite, limestone, dolomite and shale. The salt beds have a composite thickness of about 220 m in Lambton County and have been subject to dissolution with resulting thickening and collapse of overlying formations.

The salt beds of the Salina are used for product storage by several industries in the Sarnia area. These washed caverns are typically located below 600 m depth and boreholes to this depth provide potential migration pathways through overlying formations in the event of corroded or improperly constructed casings.

2.2   HYDROGEOLOGIC SETTING

The following sections summarize the reported hydrogeologic conditions of the formations in the Sarnia area and where available in Lambton County.

2.2.1   Overburden

The overburden in the Sarnia area and generally within Lambton County consists of three distinct hydrogeologic units, recent alluvial deposits, clay till and the Fresh Water Aquifer.

2.2.1.1   Alluvium.   As reported in Section 2.1.1 thick deposits of recent alluvial material consisting of silt, sand and gravel exist below the St. Clair River and overlying the clay till and bedrock. Little hydrogeologic data is available for these deposits although CN tunnel construction reports of significant sand and water inflows and gas blowouts suggest the alluvial deposits exist in the vicinity of the tunnel and have relatively high hydraulic conductivity, likely in the range 10^{-7} to 10^{-4} m/s typical for silty to clean sand (Freeze and Cherry, 1979).

Inspection reports of the tunnel completed for CN in 1948 (Singstad, 1948) and in 1978, 1980, 1981, 1982, 1983 and 1985 by Hatch Associates and Golder Associates (1978; 1980; 1981; 1982; 1983 and 1985) as well as a grouting report (International Grouting Inc., 1974) provide some direct and indirect evidence of hydrogeologic conditions in the alluvium. These reports document the quantity and quality of water pumped from the CN tunnel and from exploratory piezometers drilled from the tunnel. Analysis of these data provide an indication of the hydraulic conductivity and stratigraphy of the geologic materials surrounding the tunnel.

The above reports indicate water inflows of 112 L/min in 1892 decreasing to 3-6 L/min in the early 1980s. The reduction in inflows over this time period is attributed to successful repair of leaks to the tunnel lining in 1948 and to grouting of the surrounding soils in 1975. The best estimate of inflow prior to 1948 is 30 L/min (Singstad, 1948) which likely includes some surface water inflow from the portals. The majority of this inflow is noted (Singstad, 1948; Hatch Associates - Golder Associates, 1980; 1985) as occurring in selected locations over a 135 m section of tunnel between stations 22+50 and 27+00 which is below the St. Clair River on the Canadian side (see Appendix A1). Assuming the inflow zone as 100 m in length, and radial flow to the tunnel, the measured inflow of 30 L/min suggests a hydraulic conductivity of about 3×10^{-8} m/s. This estimate, although only approximate, is indicative of a mixture of sands, silts and clays and not solely clay till in the vicinity of the tunnel. Actual hydraulic conductivities of individual sand layers in this 135 m section of tunnel will likely have higher hydraulic conductivity because sections of clay are also reported in this 135 m section of tunnel. Observations of sands adjacent to the tunnel from exploratory borings are documented by Singstad (1948) and Hatch Associates - Golder Associates (1978). Singstad noted sand below the tunnel invert at stations 22+58 and 22+70 as well as sand to 4.5 m above the crown at station 22+58. Hatch Associates - Golder Associates (1978) also observed silts and sands in these and other locations between stations 22+50 and 27+00.

Inflow measurements made by Hatch Associates - Golder Associates during groundwater sampling of piezometers completed to the outside of the tunnel lining and deeper into surrounding soil were used to calculate hydraulic conductivity and infer soil stratigraphy (Appendix A1). Between stations 22+70 and 24+70, calculated hydraulic conductivities for the piezometers ranged from 4×10^{-11} to 1×10^{-5} m/s and the inferred soil stratigraphy was silty clay to sand and gravel. This range of piezometer hydraulic conductivities is consistent with estimated hydraulic conductivities determined from tunnel inflows.

Hydraulic gradients within the alluvial deposits surrounding the tunnel in the area of inflow are difficult to reliably quantify due to uncertainty in elevation of pressure measurement devices and integrity of the devices over time,

but available pressure measurements indicate that locally the gradients are directed toward the tunnel. This is not unexpected as the piezometers completed from the tunnel extend a maximum of 3 m or only one half a tunnel diameter into the surrounding soils.

Pressure measurements obtained in June 1982 and June 1983 in the alluvial deposits indicate approximate hydraulic heads of 170 - 180 m AMSL based on data given by Hatch Associates - Golder Associates (1985). Many of the recent 1985 pressure data were not used because the piezometers were broken and left open to drain in the period 1983-1985 and therefore the pressure measurements were unreliable particularly for those piezometers in the low permeability silt and clay tills. Piezometers completed near the floor of tunnel and in alluvial deposits and therefore likely closest to the Fresh Water Aquifer (i.e., 24+10, P2, G4, G1; 22+70, P2; and 24+70, P1, see Appendix A1 for description of location at the piezometers) indicate hydraulic heads of 170 - 175 m AMSL based on 1982 and 1983 surveys. These levels are less than the St. Clair River level of 176 - 177 m AMSL and likely less than the Fresh Water Aquifer levels in the vicinity of the St. Clair River and demonstrate the strong hydraulic drain of the CN tunnel on the surrounding alluvial deposits.

Water quality measurements performed by Hatch Associates - Golder Associates in the years 1978-1985 generally show elevated levels of chloride (>100 ppm) and phenol (>100 ppb) only in those piezometers completed from the floor of the tunnel in the alluvial deposits (i.e., 24+10, G4, P2; 24+70, P1). Appendix A1 summarizes the recent 1985 water quality analyses for the CN tunnel piezometers.

2.2.1.2 Clay Till. The hydrogeology of clay tills in the Sarnia area have been studied by researchers at the University of Waterloo and by consultants in support of studies of municipal and industrial waste sites located on the tills. A summary of the existing information on the hydrogeology of the clay till is given in GTC (1986). Desaulniers et al. (1981) and Desaulniers (1986) provide the most complete description of the hydrogeology of the clay till sequence in the Sarnia area. The clay tills in Lambton County are reported by Desaulniers

(1986) as having hydraulic conductivities of 4×10^{-11} to 1×10^{-9} m/s and porosities of 0.22 to 0.52 from laboratory and field tests. The upper 4 to 6 m of the clay tills are weathered and fractured throughout Lambton County and likely have enhanced hydraulic conductivity of 10^{-8} to 10^{-7} m/s due to fractures (D'Astous et al.,1988). The lower hydraulic conductivities of 4×10^{-11} to 1×10^{-9} m/s reported by Desaulniers (1986) are similar to calculated hydraulic conductivity based on groundwater inflow to piezometers installed in the clay till surrounding the CN tunnel (see Appendix A1).

Water table elevations in the clay till are typically within 1-2 m of ground surface in Lambton County. Desaulniers (1986) measured hydraulic gradients between surface and bedrock at five sites and estimated vertical groundwater velocities and average residence times at these five sites from measured hydraulic conductivities and porosities. These data are given in Table 2.1 and indicate very slow vertical groundwater velocities of 0.1-9.1 mm/a (4×10^{-12} - 3×10^{-10} m/s) in the clay till. Desaulniers (1986) also suggested diffusion as the dominant transport mechanism to explain the measured distribution of ^{18}O and chloride profiles and that actual fluid velocities within the tills are likely less than those shown in Table 2.1 and may be equal to zero for four of the five sites.

These studies demonstrate that the clay till is an effective confining layer above the Fresh Water Aquifer.

2.2.2   Fresh Water Aquifer

The Fresh Water Aquifer for the purposes of the following discussion is comprised of the upper 1-2 m of fractured bedrock and a thin (1-2 m) discontinuous layer of sand and gravel overlying bedrock. The Fresh Water Aquifer serves as a rural drinking water supply in Lambton County (Mellary and Kilburn, 1969) although there are no users in the immediate area of Sarnia.

Table 2.1   Vertical hydraulic gradients (i) in the unweathered
            Lambton County clay till, mean hydraulic conductivity (K),
            mean porosity (n), calculated groundwater velocities (V)
            and mean residence times (after Desaulnier, 1986)

Site	i	K^1 (m/s)	n	V (mm/a)	Residence Time (years)
Lambton I	0.18	2.8×10^{-10}	0.43	3.7	11,900
Lambton II	0.40	3.1×10^{-10}	0.43	9.1	5,000
Sarnia	0.14	2.2×10^{-11}	0.42	2.3	16,000
Sykeston	0.14	3.6×10^{-11}	0.40	0.4	100,000
Wyoming	0.01	1.6×10^{-10}	0.35	0.1	300,000

[1] Geometric mean of K values determined from water-level rise data and
    laboratory tests

Since 1973, the Ontario Ministry of the Environment have monitored drinking water supply wells in Lambton County. Appendix A2 summarizes the available analytical results for such wells proximate to the Sarnia area located in Sarnia and Moore Townships. Appendix A2 shows that the water quality in the Fresh Water Aquifer upgradient of Sarnia is variable with chloride (60-1280 mg/L), electrical conductivity (300-4200 umhos) dissolved organic carbon (<0.1-2.2 mg/L) and phenol at or below detection limits of 1 ug/L. These waters are considered to be unaffected by deep well disposal and are representative of background or average water quality within the Fresh Water Aquifer.

Scott (1986), Hyde (1987) and Sklash et al. (1986) conducted environmental isotope studies of the Fresh Water Aquifer in Lambton County and concluded that on a regional scale groundwater flow was from the east to the west across the County toward the St. Clair River. Vandenberg et al. (1977) generated a potentiometric map for the Fresh Water Aquifer in Lambton County and also concluded that on a regional scale, flow was to the west toward Lake Huron and the St. Clair River.

Erdmann (1987) performed an environmental isotope study of the Fresh Water Aquifer in St. Clair and Macomb Counties, Michigan opposite Lambton County. Potentiometric and ^{18}O data from this study showed that groundwater flow in the Fresh Water Aquifer in the U.S. side of the St. Clair River is a mirror image of that in Lambton County. These regional studies demonstrate that the St. Clair River, on a regional scale, is the major discharge point for groundwater flow in the Fresh Water Aquifer.

More regional scale hydrogeologic studies by Lane (1899), Wilson and Long (1986) and Long et al. (1988) in the east central Michigan basin identify. the area of the eastern shore of Lake Huron and the St. Clair River as regional discharge areas for near surface (<100 m) groundwater. These regional scale studies therefore confirm the St. Clair River in the Sarnia area as a major discharge area for groundwater flow in the Fresh Water Aquifer.

The hydrogeology of the Fresh Water Aquifer in the Sarnia area is described by recent studies undertaken by MOE (1985), GTC (1985, 1986), Fleming (1986), INTERA (1987a) and GLAL/Esso (1987). These studies have shown that the aquifer is patchy with an average hydraulic conductivity of 1×10^{-5} m/s and range of 4×10^{-11} to 2×10^{-3} m/s. The highest hydraulic conductivities were measured by INTERA (1987a) within the bedrock valley at the north end of EPC property and in Prince of Wales Park. In the area of the bedrock valley GLAL/Esso (1987) suggested, based on limited fluid level data, that some groundwater flow occurred downward from the Fresh Water Aquifer into the underlying permeable Hamilton limestone. Other fluid level data from EPC, MOE and EC monitoring wells (INTERA, 1987a; GLAL/Esso, 1987; Fleming, 1986) indicate that the groundwater within the Fresh Water Aquifer flows generally from east to west across the study area in the direction of the St. Clair River.

More detailed discussion of the hydrogeology of the Fresh Water Aquifer based on both previous and current monitoring well studies are provided in Section 3.

2.2.3   Kettle Point Formation

The upper 1-2 m of the Kettle Point shale is weathered and fractured. In areas where the overlying sand and gravel lenses are absent, this fractured bedrock is a source of water for domestic or agricultural purpose (Mellary and Kilburn, 1969). Hydraulic (slug) testing of MOE (Fleming, 1986) and EC (INTERA, 1987a) monitoring wells completed into the Kettle Point shale where the sand and gravel lenses are absent (i.e., wells 3-85, 4-85, 1-86, 3-86, 5-86, 6-86, 8-86) indicate bedrock hydraulic conductivities of 1×10^{-11} to 2×10^{-3} m/s. GLAL/Esso (1987) report hydraulic conductivities of 1×10^{-10} and 1×10^{-8} m/s from packer testing of sections of the shale located 5 and 1.5 m respectively below bedrock surface. The higher hydraulic conductivity measurement includes near surface fracturing and the hydraulic conductivity of the deeper sections of Kettle Point shale are estimated to be equal to or less than 1×10^{-10} m/s. Because of this low hydraulic conductivity the Kettle Point shale is considered to be a confining layer. In areas of the bedrock valley where the Kettle Point shale is eroded, this confining layer is absent.

2.2.4   Hamilton Group of Formations

Previous hydrogeologic studies of the Hamilton Group of Formations in the Sarnia area are limited to observations noted during drilling of oil, gas and cavern wells, interpretations of available geophysical logs for EPC disposal wells DW2, DW3, and DW5 and from one pumping test of a limestone layer likely within the Widder Formation by GLAL/Esso (1987).

Geophysical logs for EPC disposal wells summarized by GLAL/Esso (1987) are useful in identifying the different shale and limestone formations comprising the Hamilton Group and described previously in Section 2.1.3.   The shale sequences, particularly the massive clay shales of the Arkona and Bell Formations, are interpreted based on deep borehole testing programs of similar formations in the southern Ontario area (INTERA, 1987b, 1987c, 1988) to have hydraulic conductivity of less than 1×10^{-12} m/s.   These formations are very tight and in the absence of artificial openings such as abandoned boreholes or poorly cemented casings or natural faults or major fractures, are considered effective vertical confining layers.

The limestone layers within the Hamilton Group, particularly sections of the Ipperwash, and Widder Formations and the Hungry Hollow and Rockport Quarry Formations are likely more permeable than the shale and given the lateral continuity of several of these beds, are potential migration pathways for wastes. Hydraulic conductivities of the limestone beds based on similar formations in southern Ontario are likely to be in the range 1×10^{-10} to 1×10^{-5} m/s depending upon shale and dolomite contents.

Evidence from cavern well drilling conducted for EPC in 1967 and 1969 (Ministry of Natural Resources, Petroleum Resources Section, London, Ontario) shows that sections of the limestone within the Widder Formation at depths of 76-79 m below ground surface have significant permeability. During drilling of proposed cavern well 6, in 1967, wastes flowed from 76 m depth at a rate of 238 L/min decreasing to 80 L/min after 24 hours. In 1969, test hole 2A located 600 m east of proposed cavern well 6 flowed waste water at 10 L/min from a depth

of 78-79 m. Assuming steady radial flow and that the head driving the 80 L/min flow as between 10 and 100 m, a formation hydraulic conductivity of 7×10^{-5} to 7×10^{-6} m/s can be calculated for a 2 m length interval.

GLAL/Esso (1987) reported hydraulic testing of a permeable horizon at 72-74 m depth within the Widder Formation in the bedrock valley. This horizon contained gas and pump testing indicated a hydraulic conductivity of 1×10^{-5} m/s similar to the estimated value based on flow rates from proposed cavern well 6. It is likely that these two intervals are part of the same hydrostratigraphic unit as GLAL/Esso (1987) report this horizon to be extensive throughout the Sarnia area.

Only one fluid level measurement is available for the Hamilton Group and this measurement from GLAL/Esso (1987) is for the permeable horizon at 72-74 m depth within the Widder Formation. A fluid level of 176.37 m AMSL was recorded which was 0.89 m below the fluid level for the Fresh Water Aquifer at the same location suggesting potential for downward flow from the Fresh Water Aquifer to the Hamilton Group. The reliability of this fluid level as an indicator of hydraulic potential within the limestone is suspect however because gas production was noted from the formation and under such conditions the formation pressure will be underestimated by a fluid level measurement due to the release of gas pressure to the atmosphere.

GLAL/Esso (1987) also report water quality results for samples of groundwater collected from the Hamilton Group at 72-74 m depth. These results are given in Appendix A3 and average concentrations of selected parameters from triplicate samples were chloride - 172 mg/L, conductivity - 30,000 umhos/cm, phenol - 12,600 ug/L, oil and grease - 3.6 mg/L, ammonia - 21 mg/L and TOC - 58 mg/L. The high phenol and ammonia levels indicate that industrial waste still exists within this permeable limestone horizon in the Hamilton Group at depths of 72-74 m.

2.2.5   Dundee Formation

There is only limited data available describing the hydrogeologic conditions of the Dundee limestone. Because the formation is known to be oil and gas bearing, it is expected to have measurable porosity and permeability. McLean (1968) reported that the Dundee Formation has sporadic water shows in its lower section but that the formation did not appear to be a widespread aquifer.

Recent work by Vugrinovich (1986; 1988) in the lower peninsula of the Michigan Basin suggests that fluid flow in the Devonian and younger age rocks is gravity-driven and topographically controlled. Vugrinovich suggests that fluid flow within the Dundee Formation in the area opposite Sarnia is toward the regional discharge area of the Lake Huron basin.

2.2.6   Detroit River Group of Formations

Hydrogeologic conditions within the Detroit River Group of Formations are relatively well known in comparison to other Devonian strata due to the injection of industrial wastes and brines to the Lucas Formation. Hydrogeologic data for the Lucas Formation in Lambton County are described by McLean (1968), Vandenberg et al. (1977), URM (1984) and GLAL/Esso (1987).

The Lucas Formation has sufficient hydraulic conductivity to have been used as a disposal formation. Table 2.2, compiled from data reported by McLean (1968), URM (1984), and GLAL/Esso (1987) summarizes the measured and inferred values of hydraulic conductivity for the disposal horizons within the Lucas Formation in Lambton County. The thickness of the assumed disposal zones varied from 1 - 80 m and the corresponding values of hydraulic conductivity ranged from 6×10^{-8} to 4×10^{-5} m/s with an average value of about 2×10^{-7} m/s. URM (1984) report average injection pressures and flow rates for Lucas Formation disposal wells in the Sarnia area as 3000 kPa and 400 m^3/day. Assuming steady radial flow these data suggest, for disposal interval lengths of 5 to 50 m, hydraulic conductivities of 3×10^{-6} to 3×10^{-7} m/s, consistent with values reported in Table 2.2.

Table 2.2 Summary of Hydraulic Conductivity Estimates - Lucas Formation Detroit River Group - Lambton County

Well	Township	Date of Test	Depth of Interval Receiving Fluid (m)	Transmissivity (m²/s)	Estimated Hydraulic Conductivity (m/s)	Type of Measurement	Reference
Marcus Disposal Well #1	Enniskillen	June/70	147-163	4×10^{-5}	2.5×10^{-6}	DST*	URM (1984)
Tricil Goodfellow #2	Sarnia	Oct/74 June/75	175-213	2×10^{-5}	5×10^{-7}	DST	URM (1984)
Cambrian Disposal Ltd. #1	Sarnia	Nov/70	176-179	Very high	Very high	DST	URM (1984)
Cambrian Disposal Ltd. #2	Sarnia	June/71	173-174	4×10^{-5}	4×10^{-5}	DST	URM (1984)
CIL #1	Sombra	- - -	236-294	1×10^{-5}	2×10^{-7}	DST	McLean (1968)
Sun Oil Co. DST-1	Sarnia	June/65	213-255	2×10^{-6}	6×10^{-8}	DST	URM (1984)
Sun Oil Co. DST-2	Sarnia	June/65	214-294	6×10^{-6}	8×10^{-8}	DST	URM (1984)

Table 2.2 Summary of Hydraulic Conductivity Estimates - Lucas Formation Detroit River Group
- Lambton County (cont'd)

Well	Township	Date of Test	Depth of Interval Receiving Fluid (m)	Transmissivity (m²/s)	Estimated Hydraulic Conductivity (m/s)	Type of Measurement	Reference
Esso Petroleum Canada DW-3	Sarnia	April/60	201-282	---	9×10^{-8} to 5×10^{-7}	Laboratory Core Tests	GLAL/Esso (1987)
Esso Petroleum Canada DW-3	Sarnia	April/60	201-282	---	1×10^{-7}	Simulation of waste injection	GLAL/Esso (1987)
Esso Petroleum Canada Observation Well #1	Sarnia	1958-68	38 m thickness	3×10^{-4}	7×10^{-6}	Simulation of pressure buildup during injection period	GLAL/Esso (1987)

* DST = Drill Stem Test

Potentiometric surfaces within the Lucas Formation were compiled by Vandenberg et al. (1977), and indicated a generally westerly flow direction, however due to uncertainties in the reliability and representativeness of the data, the flow direction is uncertain. URM reported that the equilibrium fluid levels within the disposal formation are likely 0-60 m below those of the Fresh Water Aquifer and GLAL/Esso (1987) reported an equilibrium fluid level of 178.4 m AMSL for EPC disposal well DW2 which is about 5 m lower than that for the Fresh Water Aquifer in about the same location. The DW2 head value reported by GLAL/Esso is considered a composite value because it is measured over a 50 m open test interval that includes high permeability sections of the disposal zone that likely accepted most of the waste as well as other sections of the Lucas or Amherstburg units.

Groundwater quality within the Lucas Formation of the Detroit River Group is described by McLean (1968), GLAL/Esso (1987) and by MOE (1987) and summarized in Appendix A4 and Table 2.3. Appendix A4 summarizes Detroit River Group water quality data from McLean (1968), and GLAL/Esso (1987) for five locations in Lambton County. The samples from CIL disposal well #1 at 238 m and 259 m depth are from the disposal zone and the deeper sample (303 m) is likely from the Amherstburg Formation. There is considerable variability in the reported groundwater chemistry but the fluids are all high TDS, NaCl type saline waters or brines. The most saline waters are from the deepest sample listed in Appendix A4 likely collected from the Amherstburg Formation. The variability of chemistry and salinity in the Lucas Formation is probably due to regional water quality variations and differences in sampling methods and length and depth of sampling zones. The data in Appendix A4 suggest an increase in TDS and salinity with depth through the Detroit River Group of Formations.

The analytical data on Table 2.3 are for a sample of water from the Detroit River Group collected by MOE in 1986 from an abandoned oil and gas well (Prefontaine deep well) located northwest of Sykeston in Moore Township. This NaCl type water contains low levels of phenol and ammonia and may reflect injected wastes. Details of the well completion are not available.

Table 2.3   Analytical Results in mg/L (after MOE, 1987)
            Detroit River Group Formations Prefontaine Deep Well
            Sampled 1986

Chemical Parameter	Analytical Result
pH	6.71
Conductivity umhos/cm	58000
Total Dissolved Solids	45122
Alkalinity	152
Chloride	27000
Fluoride	0.98
Sulphate	2550
Sulphide	285
Calcium	1650
Magnesium	860
Calculated Hardness	7668
Sodium	22500
Potassium	175
Iron	0.60
Phenols ug/L	220
C.O.D.	800
Free Ammonia	10.4
Total Kjeldahl	10.6
Nitrite	0.02
Nitrate	0.3
Total Phosphorous	0.09
Diss. Phosphorous	0.05

On a regional basis throughout southwestern Ontario, the water quality in the Detroit River Group of Formations is quite variable (URM, 1984). In areas where the Detroit River Group subcrops (northwest of London and south of Windsor, see Figure 2.3) the Detroit River Group is an important aquifer of fresh water.

On the U.S. side of the St. Clair River, Vugrinovich (1986; 1988) recently reported on the potentiometric distribution in the Detroit River Group from oil and gas wells in a similar compilation to that of Vandenberg et al. (1977) for Lambton County. Although Vugrinovich's data is sparse in the area opposite Sarnia, the regional potentiometric surface indicates fluid flow potential to the southwest toward a potentiometric trough that runs west from the area of Lake St. Clair to Lake Michigan.

2.2.7   Bois Blanc, Bass Islands and Salina Formations

Little to no reliable information is available describing the hydrogeologic conditions of the formations underlying the Detroit River Group and to the Salina Formation in the Sarnia area. However some inferences regarding hydrogeologic conditions such as low hydraulic conductivity for the salt in the Salina Formation can be made based on observed conditions at other locations in these formations in southwestern Ontario.

Tunnel excavations undertaken by Ontario Hydro at the Bruce "A" Generating Station, located near Kincardine, Ontario and the Nanticoke Generating Station located near Nanticoke, Ontario provide evidence of the hydrogeologic conditions within the Bois Blanc Formation at relatively shallow depths of 50 m. Hydraulic conductivities of 1×10^{-9} to 1×10^{-4} m/s were reported for the Bois Blanc Formation at these sites (Hydrology Consultants Ltd., 1970; Duncan, 1970; Cohen, 1969, 1975, 1976; and Mackey, 1969). Lower hydraulic conductivities likely in the range 10^{-9} to 10^{-6} m/s are expected for the Bois Blanc Formation in Sarnia due to the increased depth and lithostatic load.

The Goderich salt mine of Domtar Inc. and the Ojibway salt mine (Windsor) of the Canadian Salt Co. intersect the Dundee, Detroit River Group,

Bois Blanc, Bass Islands and Salina Formations in southwestern Ontario. During excavation of the Goderich mine shaft significant groundwater inflows were reported from the Detroit River Group and to a lesser extent from upper sections of the Bass Islands Formation (Hewitt, 1962). The reported inflows indicate localized hydraulic conductivity of 1×10^{-8} to 1×10^{-6} m/s within the Bass Islands Formation. Inflows of up to 3000 L/min were reported by Sanford (1957), Mamen (1956) and Hewitt (1962) from shaley dolomite of the Bass Islands and upper Salina Formations in the Ojibway salt mine at 215 m depth. The reported inflows suggest hydraulic conductivity of 1×10^{-8} to 1×10^{-6} m/s for these formations.

Although zones of high permeability likely exist within the Bois Blanc, Bass Islands and upper Salina Formations, observations from the operating mine levels of the Goderich mine (about 500 m depth) and Ojibway mine (about 300 m depth) suggest the salt bearing horizons of the Salina Formation are of low hydraulic conductivity. The operating mine levels in these formations are reported as being completely dry and therefore the rocks are likely of hydraulic conductivity less than 10^{-9} m/s.

Limited data on groundwater chemistry within these deeper formations is reported by Dollar et al. (1987). Groundwaters from the Salina Formation were reported as Na-Ca-Cl type brines with TDS of 300,000-340,000 mg/L.

2.3   DEEP WELL DISPOSAL PRACTICES

Deep well disposal practices in Lambton County have been reviewed by McLean (1968), Van Everdingen and Freeze (1971), Van Everdingen (1974), Vandenberg et al. (1977), MOE (1977), URM (1984) and GTC (1985) and therefore only a brief summary of the disposal practices will be given here.

In Lambton County, deep injection wells have been used since 1958 until about 1974 to dispose of industrial wastes, cavern brines and oil field brines to the Detroit River Group of Formations. The primary focus of this study is the industrial waste disposal wells used to dispose of petrochemical and other wastes from Sarnia's Chemical Valley. Industrial waste disposal wells are

located in Figure 1.1. The wells are located primarily in the area of the petrochemical industries adjacent to the St. Clair River although some are located further inland. The most heavily utilized area (Figure 2.5) is found south of Sarnia where the wells of Esso Petroleum Canada (5 wells), Shell Canada Ltd. (2 wells), Sun Oil Company (1 well), and Polymer Corporation (1 well) are located. The Dow Chemical Co. has two wells in the same area which are situated in formations significantly deeper than the Detroit River Group and therefore are not specifically of concern in this study.

Details of the industrial waste disposal wells are summarized from URM (1984) in Table 2.4. The disposal wells typically have total depths ranging from about 200 to 300 m below surface. The injection zone usually begins in the base of the Dundee Formation and extends through the Detroit River Group and bottoms in the top of the Amherstburg Formation at depths from about 150 to 300 m. While the injection intervals are long the majority of flow from the disposal well may occur from a lost circulation zone. These zones are usually thin (i.e., approximately 1-10 m) and caused by vuggy porosity and solution weathering.

Injection pressures at the well head during disposal operations typically ranged from 0 to about 3000 kPa. Wells close to the River generally required high injection pressures because of low formation permeability in this area whereas further inland the waste was allowed to flow to the formation under gravity feed. Because of the low formation permeability in the area close to the River, a number of these wells were acidized and in some cases hydraulically fractured to increase the formation permeability and to reduce the injection pressure.

The types of wastes injected were generally spent caustics and phenolic waters. More specific details of the chemical nature of the disposal fluids are given in Section 2.3.1. It is estimated that over 8,000,000 m^3 of waste have been injected into the Detroit River Group in the period 1958 to 1974 (URM, 1984).
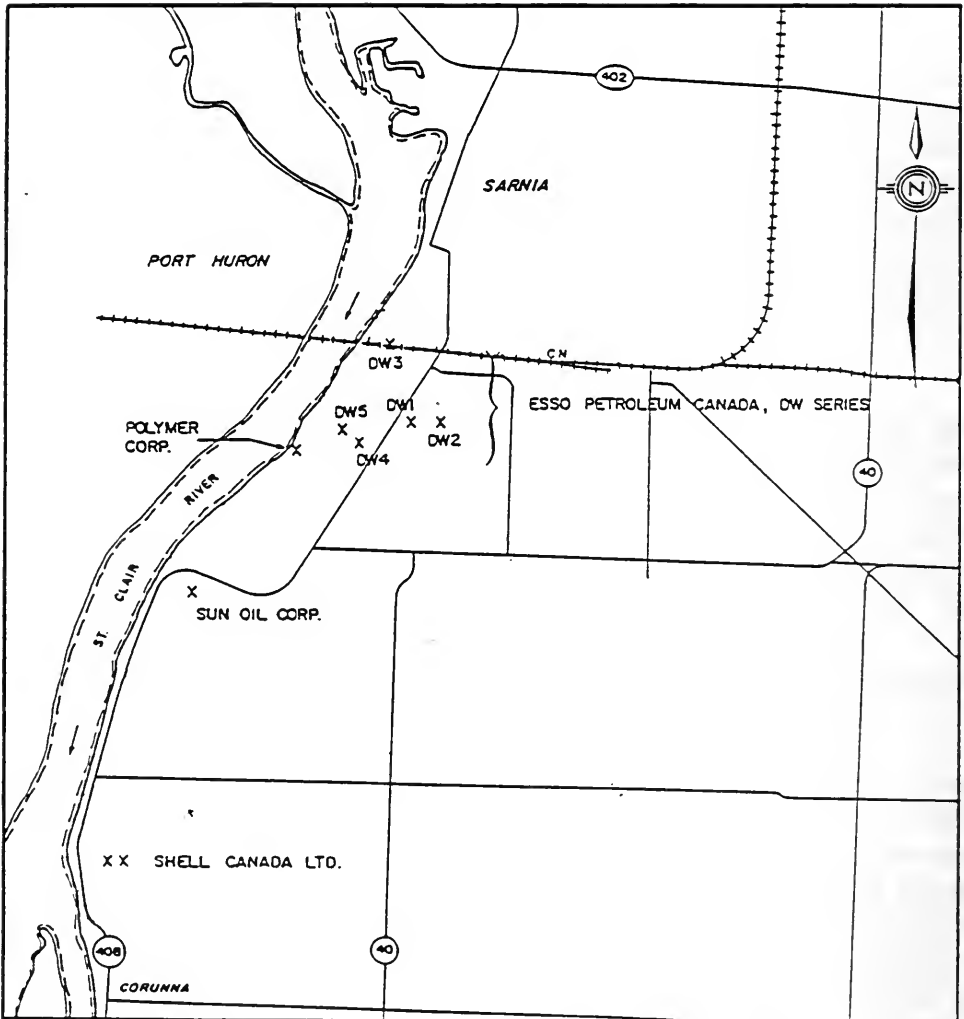
LEGEND

X ——— INDUSTRIAL WASTE DISPOSAL WELLS TO DETROIT RIVER
GROUP OF FORMATIONS

Drawn by	Date
Checked by	Date
Revisions	Date

LOCATION OF INDUSTRIAL WASTE DISPOSAL
WELLS IN THE STUDY AREA

SCALE 0 1 2 3 km

FIGURE 2.5

Table 2.4 Industrial Waste Disposal Wells in Lambton County (after 1964, 1984)

Company Well Name	Location County	Twp	Conc	Lot	Well Head Elevation ft (m)	Total Depth ft (m)	Injection Zone Interval ft (m)	Maximum Well Head Pressure psi (kPa)	Average Injection Rate bbls/day (m³/day)	Period of Injection	Total Injected bbls (m³)	Major Type of Waste
Kaiser Disposal Well #1	Lambton	Enniskillen	5	31	675 (206)	961 (293)	Detroit River Gr. 488-689 (149-210) 545-580 (166-177)	0 to 150 (1034)	740 (118)	1970-1971	270,000 (42,927)	Spent Caustic, Industrial Waste
Thompson Right Company 2 Wells	Lambton		12	12	670 (204) 673 (205)	852 (260) 1000 (305)	550-852 (168-260)	50 50	118 (18.8)	1965-1974 1969-1974	490,000 (71,900)	Acid, Caustic, Brine, Oily Water
Tricil Goodfellow #1 #2 2 Wells	Lambton	Moore	10 10	9 9	664 (202) 661.4 (202)	597 (182) 700 (213)	573-700 (175-213)	0 0	300 (47.7) ?	1958-1973 1973-1976	1,979,000 (314,636)	Hydrocarbons, Chlorides, Ethers, Phenols
Shell Canada Limited #1 #2			Prov. Prov.	68 48		950 (290) 950 (290)	600-900 (183-274) 650-950 (198-290)	330 (2275)	1500 (238)	1962-1972 Not utilized	6,260,000 (995,260)	Phenols
Sun Oil Company	Lambton	Sarnia	18	19		964 (294)	675-964 (206-294)	300 (2068)	1900	1965-1973	3,450,000 (548,506)	Spent Caustic
Polymer Corp.			Reg. Plan 12	35		900 (274)		450 (3103)	213 (302)	1961-1970	700,000 (111,291)	Spent Caustic, Phenols
Imperial Oil Ltd. 5 Wells #1						800 (244)	605-800 (184-244)	370 (2551)	1200 (191)	1958-1967	30,362,000 (4,827,000)	Spent Caustic, Phenols, Sulfides
#2						820 (250)	605-820 (184-250)	100 plus 370 (2551)	1200 (191)	1960-1967		
#3						675 (206)	629-675 (192-206)	400-450 (2758-3103)	300 (52.4)	1960-1972		
#4						820 (250)	635-820 (194-250)		2510 (402)	1961-1972		
#5						820 (250)	635-820 (194-250)		2080 (330)	1961-1972		
Canadian Industries Ltd. 2 Wells #1 #2	Lambton	Sombra	15 15	2 4	607.5 (185)	1249 (381) 1219 (370)	775-1234 (236-376) 790-840 (241-256)	370 (2551) 100 plus 370 (2551)	1200 (191) 1200 (191)	1968-1972	3,750,000 (596,202)	Steam Condensate with ammonia and CO₂
Dow Chemical 2 Wells	Lambton	Sarnia	18	29 10			Cavern, Salina Salt 1900'	0		1960-?	4,000 (636)	Waste Oils Solid CaCO₃ residue

2.3.1   Chemical Composition of Waste Fluids

The chemical composition of waste fluids disposed to the Detroit River
Group is poorly documented. Available information is found in annual and monthly
summary reports provided to the Ontario Department of Mines and Northern Affairs
by the disposal companies. These reports, started in about 1968, list the
chemical composition of the wastes but provide very little detail beyond the
major components. Available chemical information for fluids disposed to the Esso
(GLAL/Esso, 1987), Sun Oil, Shell Canada, and Polymer Corp. wells is given in
Appendix A5. GLAL/Esso (1987) provide a brief discussion and chemical analyses
for the five Esso disposal wells with a summary (Table 2.5) of the composition
from 1964 to 1986.

In general, the Esso wells received primarily spent caustics and
ammonical water from the chemical plant and phenolic waters from the refinery
that were characterized by high pH and alkalinity, elevated phenols and low
chloride concentrations (GLAL/Esso, 1987). Similarly the Sun Oil disposal well
received refinery phenolic and sour waters, neutralized acids and caustic wastes
characterized by high alkalinity, total and dissolved solids, ammonia and H_2S and
elevated phenols. The Shell Canada disposal well received water soluble
compounds leached from crude oil fractions and cracked products and typically
contained high H_2S and elevated phenols. The Polymer Corp. well was used to
dispose of spent caustics consisting mostly of sodium hydroxide and sodium
hydrosulphide.

2.3.2   Historical Occurrences of Breakouts

With high injection pressures it is possible for disposed wastes to
leave the disposal zone via a number of failure pathways. The potential fracture
pathways are illustrated in Figure 2.6 and include the following (GTC, 1985):

> o   Numerous boreholes from oil and gas wells exist in the area.
>   These boreholes, many of them abandoned and unplugged, provide
>   open conduits through the bedrock confining units;

TABLE 2.5 **RANGES OF CHEMICAL CONCENTRATIONS OF WASTES INJECTED IN ESSO WELLS INTO THE DETROIT RIVER GROUP OF FORMATIONS** (from GLAL/Esso, 1987)

CHEMICAL PARAMETERS	DATE							
	1964	1966	1967	1969	1970	1971	1972	1986*
Hydrogen Sulphide	2500	500-12000	500-12000	50000	9000	--	--	130
pH	12.5	9.0-12.8	9.0-12.8	--	--	--	--	12.0
phenol	85	100-2000	100-2000	7.5-150	100-150	100-150	100-470	140
HCN	--	0-5	0-5	--	--	--	--	
Alkalinity	--	1000-12000	6000-50000	--	--	--	--	6100
Sodium (Na)	4900	12-1000	12-1000	--	--	--	--	
Mercaptans	--	1000-1000+	1000-1000+	--	--	--	--	
NaOH	--	--	--	50000-1000000	9000-20000	9000-100000	3500-100000	
Na Phenolate	--	--	--	100	20	50	--	
Na Sulphide	--	--	--	41000	8000	100-40000	3500	
Sulphide	--	--	--	10-12000	30-100	30-40000	0-4000	
Ammonium Hydroxide	--	--	--	--	1100	--	--	
Chloride	<20	--	--	--	--	--	--	5900

NOTE: All analyses in mg/L
* 1986 data based on samples pumped from DW2
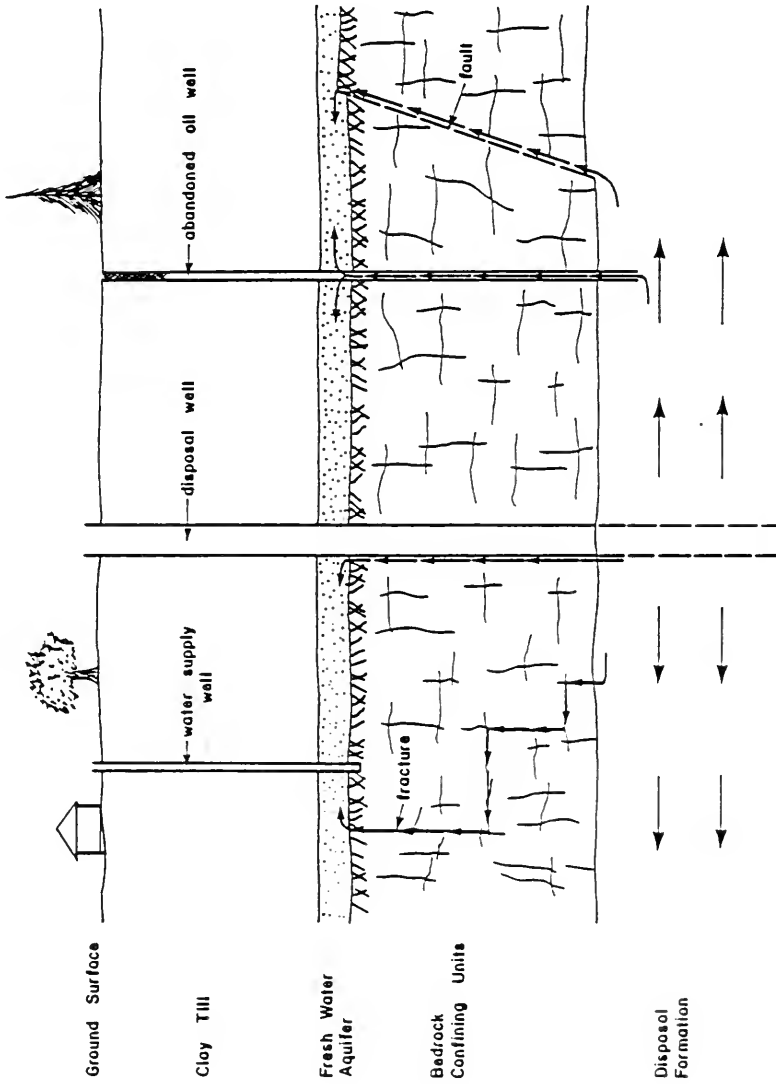
SCHEMATIC ILLUSTRATION OF POTENTIAL DISPOSAL WELL FAILURE PATHWAYS

FIGURE 2.6

- Poorly constructed injection wells or cavern storage wells that allow waste to migrate along the outside of the casing;

- Faults, fractures and joints are likely to exist in the bedrock confining units. Although the degree of fracture continuity in these units is unknown, it is possible that pressurized wastes could travel great distances via these fractures;

- The vertical permeability of the confining shale and limestone units may be of significant magnitude to allow pressurized wastes to migrate via the pore spaces to the Fresh Water Aquifer.

The low intrinsic vertical permeability of the shale and limestone confining units likely prevent migration of the wastes via the pore space and therefore this method may not be as significant as the other three. The abandoned oil and gas wells are the most probable failure mechanism in this area because of the long history of oil and gas exploration and the numerous boreholes drilled in the area. Many of the exploration boreholes were not properly abandoned (i.e., cemented to surface) and therefore the boreholes may be open from the disposal zone to the surface. Poorly constructed injection wells or cavern wells may result in failure if the steel casing and/or casing cement has been corroded or eroded by acidic or caustic industrial wastes.

Many industries located along the St. Clair River use deep underground caverns in the Salina Formation for product storage. The wells connecting the caverns to surface are considered potential fluid conduits between the disposal zone and shallower geologic formations including the Fresh Water Aquifer. Although not specifically located in this report such cavern wells exist on Esso Petroleum Canada, Polymer, DOW, Sun Oil Corp. and Shell Canada property.

These failure pathways, especially the abandoned oil and gas wells and casing/cement failures, have resulted in a number of breakout wells (i.e., abandoned wells suddenly flowing at surface) in the Sarnia area. The breakout wells do not necessarily flow industrial wastes but the fact that an abandoned

well would start to flow indicates that the groundwater system has been pressurized above its natural state. The breakout wells are reported in McLean (1968) and URM (1984) and are summarized from GTC (1985) as follows:

- 1966 - Esso Petroleum Canada, Sarnia, an old borehole flowing phenolic wastes was located and plugged;
- 1967 - Esso Petroleum Canada, Sarnia, Possible water well (?);
- 1967 - Port Huron, Michigan, at least seven wells one of which contained trace phenols and H_2S;
- 1967-1970 - CIL near Courtright, two deep wells within 1.8 km and one deep well 3.7 km southeast and shut-in pressure of 96.5 kPa with trace waste;
- 1970 - Marine City, Michigan, across from CIL, two oil and gas wells flowed brine and an abandoned deep well flowed at surface;
- 1972 - Capital Theatre, Sarnia, confirmed industrial waste at 27 to 54 m^3/day for well reported 43 m deep (MOE memorandum T. Yakutchik to W. Williamson, November 26, 1972);
- 1972 - Imperial Oil Enterprises Ltd., Sarnia, two wells one of which was 40 m deep (MOE memorandum T. Yakutchik to W. Williamson, November 26, 1972) confirmed industrial waste.

Most of the breakouts have been attributed to abandoned oil and gas wells, however, some of the breakouts (i.e., Capital Theatre, Esso Petroleum Canada) appear to be from Fresh Water Aquifer wells. It is possible that these shallow wells may have been converted from deeper oil and gas wells (i.e., Capital Theatre) or may have been hydraulically connected to a disposal well via a break in the casing in the Fresh Water Aquifer (i.e., Esso Petroleum Canada well).

Chemical analyses of some of the breakout waters are reported in Appendix A5. Water quality results are available for the Capital Theatre well, the Esso breakout wells and two of the eleven breakout wells in Port Huron, Michigan. The Esso and Capital Theatre wells were found to contain high (500,000

ppb) and elevated (2,000 ppb) levels respectively of phenols (OWRC, 1972, Appendix A5) which indicates the presence of industrial wastes. The two Port Huron wells, although they contain low levels of phenols (i.e., 20 and 250 ppb) and one has high levels of sulphide as H_2S (1,000 ppm) can not be reported conclusively to contain industrial wastes.

In addition to these flowing wells, two occurrences of waste flow at surface during drilling of cavern wells was also reported. Drilling by Esso Petroleum Canada in 1967 and 1969 of proposed cavern well 6 and test hole 2A flowed industrial waste at rates of 10-238 L/min from depths of 76-79 m (i.e., from within the Hamilton Group).

3. FRESH WATER AQUIFER INVESTIGATIONS

3.1 FIELD METHODS

3.1.1 Health and Safety Program

Prior to the start of any field work in the Sarnia area, a health and safety plan was developed to ensure safe and healthy working conditions and practices on this project. The health and safety plan complied with the Occupational Health and Safety Act and the Workman's Compensation Act and was administered by the INTERA Health and Safety Officer. All field workers and subcontractors were instructed in the protocols of the plan and the proper use of monitoring and personal protective equipment.

Potential hazards in this project included methane (and possible hydrogen sulphide) gas and exposure to industrial waste during drilling, testing and sampling of the Fresh Water Aquifer and to a greater extent with the deep borehole. Safe drilling practices, site monitoring, personal protective equipment, and on-site control and handling of waste materials were used to ensure a safe and healthy work environment throughout this project. The following paragraphs provide descriptions of the components of the health and safety plan implemented for the study of the Fresh Water Aquifer.

Personal protective equipment for each worker was required when working in the immediate vicinity of the drilling equipment and/or near an existing monitoring well. The protective gear was generally at Personnel Protection Level C (Table 3.1) for most of the drilling operations but was to be upgraded as required. At this level, an air purifying respirator and dermal protection are required. The protective clothing included:

- Tyvek coveralls;
- Chemical resistant boots or overboots;
- Safety goggles/glasses (as appropriate);
- Hard hat;

Table 3.1   Levels of Protection for Hazardous Work Incidents

Level of Protection	Situation	Equipment
Level A	High potential hazard of dangerous fumes; High potential hazard of skin/eye contact.	• Fully-encapsulated chemical-resistant suit • Supplied-air respirator (worn inside suit) • Inner gloves • Chemical-resistant boots with steel-toes and shanks.
Level B	High potential hazard of dangerous fumes; Low potential hazard of skin/eye contact	• Chemical and/or fire-resistant protective clothing, with hood • Supplied-air respirator • Inner and outer gloves • Chemical-resistant boots with steel-toes and shanks.
Level C*	Low potential hazard of dangerous fumes; Low potential hazard of skin/eye contact.	• Chemical and/or fire-resistant protective clothing • Air-purifying respirator with canister/cartridge • Outer gloves • Chemical-resistant boots with steel-toes and shanks • Safety glasses or goggles.
Level D	No possible hazards of contamination.	• Hard hats • Coveralls • Steel-toed boots • Safety glasses or goggles

*The drilling and monitoring well work was performed at a modified Level (Low Level C). That is, respirators were immediately available to all personnel but were not worn unless indicated by adverse breathing space conditions.

- Air purifying respirator equipped with organic
  vapour/acid gas cartridges with a toxic dust prefilter;
- Gloves - surgical and chemical resistant.

A "field work area" was defined as a 10 m area surrounding the actual drilling operation or the new well installation and its related equipment. No smoking, drinking, eating or ignition of flammable liquids was allowed within the work area. The work area was defined by fencing to secure the area and the working surface was covered with a plastic sheet and plywood. No one was allowed in the working area without the proper safety equipment. Monitoring of the work area was conducted on a regular (hourly) basis using an explosimeter or combustible gas indicator and an organic vapour detector. During all drilling and well development operations, routine monitoring of the air at the borehole and within the work area was performed to detect unsafe working conditions. Monitoring of all soil samples and rock core was similarly conducted.

An unsafe working condition was defined as:

- explosivity reading of 10% LEL (Lower Explosive Limit) or greater;
- organic vapour reading greater than 5 ppm above background;
- noxious odours.

Should any of these conditions arise in a worker's breathing space as a result of a field operation, that field operation was to be suspended and the site safety officer (or his designate) notified. The hazard level was to be assessed by the safety officer using further monitoring. If the hazard had dissipated, the field operation continued with the monitoring frequency increased to a 15 minute interval for a minimum of two hours. Personal Protection Level would also be increased to a full Level C. If the hazard persisted, the Level of Personnel Protection was increased to Level B until monitoring for a two hour period no longer detected a hazard.

During drilling and sampling of the Fresh Water Aquifer monitoring wells, no unsafe working conditions were encountered and these activities were performed at a modified Level C of protection.

All work on industrial properties was performed in accordance with existing industrial safety regulations and required standby self-contained breathing apparatus for workers. All field workers completed the appropriate safety courses for each industrial site. Details of safe drilling practices and decontamination procedures and on-site control and handling of waste materials for the Fresh Water Aquifer investigations are described in Section 3.1.2.

3.1.2   Drilling, Monitoring Well Completion and Well
        Development

Prior to the start of any drilling, an equipment decontamination pad was constructed on the property of the Sarnia Sewage Treatment Plant located at 333 St. Andrew Street in Sarnia. The decontamination facility was required to prevent cross contamination of boreholes by drilling equipment, and to prevent the spread of potentially contaminated materials. The facility consisted of an asphalt pad large enough to accommodate the drill rig and any vehicle that might become contaminated, a drainage sump and a high pressure hand held jet washer for cleaning all equipment. The asphalt pad prevented infiltration and runoff of contaminated water and directed these to the drainage sump. All material collected in the drainage sump was pumped to storage tanks and, based on contaminant levels, this water was either discharged to a sanitary sewer or registered as a hazardous waste and disposed at Tricil.

The facility also included drums for the disposal of soiled clothing and storage for outer work boots, respirators, gloves, etc.

The drilling and all related drilling equipment was thoroughly cleaned at the decontamination facility prior to drilling the first monitoring well and subsequently between wells.

Approval for drilling and installation of monitoring wells was obtained from all property owners and the Ontario Ministry of the Environment prior to commencement of drilling. Site surveys for determining the location of all underground utilities including telephone, electrical, gas, cable television, water and sewer were also performed prior to drilling.

A mud rotary method was used to drill boreholes to the Fresh Water Aquifer. Mud rotary drilling, using a mixture of drilling mud and Sarnia city water, was selected as a drilling method because the dense drilling fluid assisted in preventing natural gas from blowing out the well.

Mud rotary drilling was used to advance boreholes through overburden and into the bedrock. A surface casing was installed for the start of each borehole to prevent drilling fluid loss in the shallow overburden. Drilling fluid was tagged with a fluorescent dye tracer (Lissamine FF) and a salt tracer (Iodide) and sampled to distinguish between drill water and groundwater in subsequent well development and groundwater sampling programs. Drill cuttings were logged to provide a stratigraphic log for each borehole.

At a depth of 1.5 m into bedrock, the drilling operation was completed and the borehole was flushed with clean, traced water prior to the installation of the well screen and standpipe. The well installation consisted of a 3.0 m length, 51 mm diameter, 10-slot, flush threaded, PVC, TriLoc well screen attached to 3.0 m lengths of 51 mm diameter, flush threaded, PVC, TriLoc pipe. The well screen was sand packed into place with a well sorted quartz sand. The sand pack extended to about 0.6 m above the well screen. A bentonite seal, approximately 1.0 m thick was placed on top of the sand pack to isolate the well interval. The remainder of the borehole was grouted to surface using a Portland cement and bentonite mixture which was injected into the bottom of the borehole using a tremie pipe. A protective steel surface casing and a locking well cap was installed at surface around each well.

At all times during the drilling and well installation, the water or mud level in the borehole was kept close to surface to prevent gas production in the well.

Well development was completed using a combination of hydraulic jetting and surging. The jetting method consisted of a stainless steel jetting tool that was slightly smaller in diameter than the inside diameter of the piezometer. Well development was performed by injecting Sarnia city water (tagged with

Lissamine FF and Iodide tracers) at high pressure (approximately 680 kPa) into the well screen. The jets agitated the sand pack and drew fine grained material into the well screen where it was flushed to ground surface. During jetting, the jetting tool was quickly moved up and down in the well screen creating a surging effect. Well development continued until the return water was clean.

If the well did not produce gas at any time during drilling or well development, the piezometer was air lift pumped to remove standing water in the well.

During well development, a record was kept of the injected volume and the return volume in order to determine the volume of water lost to the formation. All water used in the well development process was tagged with Lissamine FF and Iodide tracers and sampled. The tracer served as an indication of the level of foreign water remaining in the groundwater during geochemical sampling.

Tracer concentrations in drill water, development water and sampled water were made in the field using a Turner Model 111 field fluorometer with appropriate filters and an Iodide specific ion electrode and meter.

Fifteen monitoring wells numbered 1-87 through 15-87 were completed in this study in the period August 8 to September 12, 1987.

3.1.3   Geophysical Logging

Geophysical logging was performed in five boreholes (1-87, 2-87, 6-87, 12-87, and 14-87) to provide stratigraphic information. The logging was performed by the Groundwater Research Group, Scarborough Campus, University of Toronto and included the following logs: self potential, 16" normal resistivity, 64" normal resistivity, single point resistance and natural gamma. A gamma-gamma log was not attempted in the holes due to the risk of borehole collapse and the consequent potential loss of a radioactive source. Fluid logs were not

run as the logging was performed immediately after drilling when the hole contained drilling mud which was totally unrepresentative of formation conditions.

3.1.4   Hydraulic Conductivity Testing and Water Level Monitoring

Each of the fifteen new Fresh Water Aquifer wells were tested to determine the hydraulic conductivity of the aquifer in the vicinity of the well. The hydraulic conductivity testing was conducted by several methods including slug, pump, recovery and withdrawal tests.

The slug test was the standard testing method and was completed in most of the piezometers. In this test, a volume of water was quickly removed from the well. The water level in the piezometer was then monitored until it recovered back to its equilibrium level. The rate of water level recovery was used to estimate the hydraulic conductivity by the Cooper method (Cooper et al., 1967).

A pump test was completed on the 102 mm diameter pump well installed in Prince of Wales Park in 1986 by Environment Canada (INTERA, 1987a) and hydraulic conductivities were determined from adjacent MOE, EC and EPC monitoring wells. The pumping well was pumped at 590 L/min and wells were monitored for water level response for 12 hours with the recovery of piezometers monitored for 24 hours after the pump was turned off. Results of the pump test were analyzed using the Theis (1935) solution to determine an aquifer hydraulic conductivity.

Recovery tests were conducted on 1985, 1986 and 1987 monitoring wells that were very slow to recover to a static water level. These wells, because of their low hydraulic conductivity could not be adequately tested using the slug test method. The recovery tests were completed by dramatically lowering the water level in the well by air lift pumping. The long term water level recovery

of the wells was monitored over a period of weeks to months. The recovery data were analyzed by determining an average flow rate and drawdown from selected water level measurements and expressing these data as hydraulic conductivity assuming steady confined radial flow.

The final test method, withdrawal tests were conducted to confirm the slug test results in selected monitoring wells. Confirmation of slug test results was required because the slug tests were thought to preferentially measure the hydraulic properties of the sand pack surrounding the well screen and therefore may not be representative of the conditions in the Fresh Water Aquifer. By removing a larger volume of water in the withdrawal test, the withdrawal test is more likely to measure the hydraulic properties of the Fresh Water Aquifer. In the withdrawal test, the piezometers were pumped at a low rate using a peristaltic pump. The pump rate and the water level drawdown were monitored until both reached steady state. Steady state (i.e., a relatively constant water level and flowrate) was typically reached within one hour of the start of the test. The results of the tests were analyzed assuming steady confined radial flow.

Water levels were monitored in each well using an electric water-level tape accurate to 0.01 m. The depths to water level were expressed as elevations above mean sea level using the elevation of the top of the well casing. Water level surveys were performed intermittently throughout the drilling, well development and first groundwater sampling round. Complete water level monitoring of all wells in the Fresh Water Aquifer including 1985 MOE wells, 1986 Environment Canada wells, 1986 EPC wells and 1987 MOE wells was performed on October 9, 1987, January 19, 1988, March 4, 1988, March 21, 1988 and May 31, 1988. During these surveys water level data were collected from 39 monitoring wells. Water level data for EPC monitoring wells were measured and expressed as water level elevations by EPC.

3.1.5   Groundwater Sampling

The MOE and EC Fresh Water Aquifer wells were all sampled using established groundwater sampling protocols.   The protocols documented the procedures for well purging, sampling equipment, field analytical methods, sample collection and preservation and sample identification, control and handling. Table 3.2 summarizes the field sampling requirements for analysis of waters collected from the Fresh Water Aquifer.

Because the monitoring wells in the Fresh Water Aquifer were drilled by mud rotary, it was necessary to purge residual drilling fluid and well development water from the test zones prior to sampling.   These fluids were tagged with the fluorescent dye Lissamine FF and Iodide. The concentration of Lissamine FF and Iodide was monitored during purging to determine residual drilling fluid contamination in the water samples.

Both purging and sampling of the Fresh Water Aquifer wells were conducted with Geoguard two-stage pumps which were permanently installed in each of the wells to the top of the well screen. During nitrogen-lift purging of the wells with the pumps, purge water samples were collected and analyzed for Lissamine FF and Iodide. Purging continued until the tracer concentration was reduced to low levels (i.e., less than 5% of input or drill water concentrations). Prior to initial sampling, typically 5 - 10 well volumes were purged from the new wells and the previously installed but unsampled 1986 Environment Canada wells, and three well volumes from the existing 1985 MOE wells. Purge volumes of about three well volumes were typically removed from each monitoring well prior to second and third round sampling events. If the transmissivity of the well was low and three well volumes could not be removed, the fluid level in the well was lowered to the pump and the well was sampled during recovery of the fluid level to equilibrium levels.

Table 3.2   Field Sampling Requirements - Fresh Water Aquifer

Analytical Laboratory	Parameters	Sample Containers	Sample Preservation	Sample Filtering
Field Measurement	Lissamine FF, I	1-100 mL Plastic	4^oC	Yes
Field Measurement	pH, Conductivity, Temperature	Flowcell	---	No
MOE London	Fe, Ca, Mg, Na, K, CO_3/HCO_3, SO_4, Cl, F, NO_3, NH_3	1-500 mL Plastic	4^oC	Yes
MOE Rexdale	Metals	1-500 mL Plastic	None 4^oC	Yes
MOE London	Phenols	1-Glass Phenol Bottle	$CuSO_4$ 4^oC	Yes
Barringer Magenta Ltd., Rexdale	Purgeable (volatile) Organics	2-60 mL VOA Bottles	4^oC	No
	Acid-Base Neutral Extractables	2-1L Amber Glass	Neutralize to pH 7-10 4^oC	Yes
	Organochlorine Pesticides and PCBs	1-1L Amber Glass	Neutralize to pH 6-8 4^oC	Yes
*University of Waterloo	^{18}O, ^2H, ^3H	1-125 mL Plastic	4^oC	Yes

*Collected only during first sampling round

The dedicated Geoguard bladder pumps were used to collect samples from the Fresh Water Aquifer following purging of residual drilling fluid/development water. This pump is constructed of a PVC and stainless steel body and a teflon bladder. The water level in the casing was monitored during pumping with a clean electric water-level tape to ensure adequate pump submergence. Pumping rates were measured using a calibrated discharge collection container and stop watch. All information concerning purged volumes, pumping rates, and water levels were recorded in a field log book.

During pumping of the well for sampling, the following geochemical parameters were monitored in the field: pH, temperature, electrical conductivity/salinity, and the drill fluid/development water tracers Lissamine FF and Iodide. All field analyses were recorded in the field log book.

During pumping a portion of the discharge water was directed to a flow cell where the pH was measured using a Cole Parmer combination pH electrode and a Digi-Sense pH meter. The pH electrode was calibrated with pH 7 buffer and pH 4 or 10 buffer solutions at the groundwater temperature.   A Yellow Springs conductivity meter and electrode were used to determine electrical conductivity, salinity and temperature.   A standard salt solution was used to calibrate the electrode prior to sampling.

Three sampling rounds of the Fresh Water Aquifer were conducted in this study. The first sampling round was performed in the period September 10 - November 5, 1987, the second round, January 20-27, 1988 and the third sampling round, March 21-30, 1988. During the first sampling round filtering of water samples, pH and conductivity measurement and filling of sample bottles was performed at the monitoring well site. During the second and third sampling rounds cold weather prohibited this activity and unfiltered water samples were collected in 4 L amber glass bottles at the well and transported to the INTERA field office and laboratory for filtering, pH and conductivity measurement and filling of sample bottles.

Samples for major cations and metals were filtered through 0.45 um cellulose membrane filters either with disposable nalgene filter units or with in-line nalgene filter holders. Filtrates were collected in new 500 mL nalgene LPE sample bottles. Metal samples were acidified to pH<2 with nitric acid. Major cation samples were not acidified. All samples, both inorganic and organic were refrigerated during storage and transported in coolers to the appropriate laboratory.

The following cations and metals were analyzed according to the Handbook of Analytical Methods for Environmental Samples, Ontario Ministry of the Environment (1983): Ca, Mg, Na, K, Fe, Mn (by MOE London laboratory), and Cu, Ni, Pb, Zn, Mn, As, Cd, Co, Cr, Mo, Se, Sr (by MOE Rexdale laboratory).

Samples for anion analyses were also filtered through 0.45 um filters and collected in new 500 mL nalgene LPE bottles. The following parameters were analyzed by the MOE London laboratory according to the MOE Handbook of Analytical Methods for Environmental Samples: pH, carbonate/bicarbonate, alkalinity, sulphate, chloride, fluoride, ammonia, and nitrate.

All samples for organic analyses were collected in precleaned glass containers provided by the laboratory. Organic analyses included total phenols, by MOE London and base neutral/acid extractables, purgeable organics and organochlorine pesticides and PCBs all by Barringer-Magenta, Rexdale. The analytical methodology and laboratory quality control program followed by Barringer-Magenta is given in Appendix B.

Samples for phenol analysis were collected in MOE glass bottles, preserved with $CuSO_4$ and analyzed by the 4AAP method (MOE Handbook of Analytical Methods for Environmental Samples, 1983).

Samples for base/neutral and acid extractables had their pH adjusted to within the 7 - 10 range, if necessary, through addition of NaOH or H_2SO_4 and the volume of acid or base recorded. Bottles were not pre-rinsed with the sample water. Lab analytical methods conformed to a modified EPA Method 625, (Federal Register Vol. 44, No. 233, p. 69540-69548, 1979).

Samples for organochlorine pesticides and PCBs had their pH adjusted to the 6 - 8 range with NaOH or H_2SO_4. Bottles were not pre-rinsed with the sample water. The method of analysis conformed to a modified EPA Method 608 (Federal Register Vol. 44, No. 233, p. 69501-69509, 1979).

Samples for purgeable organics were collected in such a fashion that they had little contact with the atmosphere. For wells in the Fresh Water Aquifer, a teflon "T" coupling and valve was attached to the pump discharge tube to enable the sample container to be gently filled without allowing air entry into the sample. If free chlorine was present in the water, sodium thiosulphate was first added to the sample bottle. Purgeable organics were analyzed according to EPA Method 624 (Federal Register Vol. 74, No. 233, p. 69532-69539, 1979).

According to the EPA methods, purgeable organic compounds were analyzed within 7 days of collection. Compounds analyzed by EPA Methods 608 or 625 were extracted within 7 days and analyzed within 30 days.

Each collected sample was clearly identified with an attached label bearing the following information:

- date and time of sample collection;
- sample number and lab number (to be assigned by the laboratory upon receipt of sample);
- well number and in the case of the deep borehole the sample depth interval;
- sample type (inorganic/cations, organic/purgeable organics, etc.);
- sampling method;
- preservation technique (if any);
- sampler's signature.

A sampling record log was kept to record all the necessary sampling information that is important to the interpretation of the analytical results.

A chain of custody record was completed for each sample shipment by the field sampler and accompanied the samples during their transport from the sampling site to the laboratory. This form recorded custodian responsibility for the samples each time possession of the samples were transferred and until they were received and signed for by the laboratory. Samples were only shipped by a reliable courier and only when next-day delivery could be guaranteed.

3.1.6   Sampling and Analytical Quality Assurance/Quality
          Control Program

Field sampling and laboratory analytical quality assurance/quality control (QA/QC) programs were established to ensure that the geochemical results were representative of the in situ conditions and to quantify the accuracy and precision of the analyses. The field QA/QC sampling program included:

- equipment blanks;
- trip blanks;
- duplicate samples.

Following cleaning of the sampling equipment, equipment blanks were prepared by rinsing the equipment with deionized water and collecting the rinse water for analysis. Equipment blanks were prepared during each sampling event. Blanks were collected from the dedicated sampling pumps but only once prior to their installation in the well.

Trip blanks were used to determine if any contamination of the sample bottles occurred during shipment and storage of the samples. The blanks were prepared by the laboratory and consisted of bottles filled with distilled, deionized water containing any preservatives added by the laboratory. They were shipped with the sample bottles to the field site and accompanied the other bottles during sample collection, storage, and return shipment to the laboratory. At least one trip blank set was used for each sampling methodology for each sampling event.

Duplicate samples were collected at a frequency of 1 duplicate set for every 10 sample sets and these were used to determine the precision of an analysis as defined by the relative percent difference between measured duplicate samples. Each duplicate was a blind duplicate in that the duplicates were not identified to the laboratory.

A laboratory QA/QC program (Appendix B) was implemented by Barringer-Magenta for the organic analyses. This QA/QC program included the use of:

- repeat analyses;
- laboratory reagent blanks:
- spiked sample analyses;
- surrogate standard analyses for all samples.

Repeat analyses indicated the precision of the analytical method. Laboratory blanks identified any laboratory-introduced contamination to the samples during the analytical procedure. Spiked samples were used to quantify accuracy of the analytical method by adding known concentrations of all compounds to be analyzed by a particular method to both distilled water and samples. Recovery of selected surrogate standards was also monitored in each analysis to quantify the reliability of the analysis.

3.2   RESULTS AND INTERPRETATION

3.2.1   Monitoring Well Network

Figure 3.1 shows the location of the monitoring well network for the Fresh Water Aquifer established by the Ontario Ministry of the Environment, Environment Canada and the Ontario Ministry of the Environment in 1985, 1986, and 1987 respectively. Table 3.3 summarizes the location and completion details of these monitoring wells. This MOE and EC well network consists of 29 monitoring wells for the Fresh Water Aquifer and one water table well in Prince of Wales Park (2-86). All wells except wells 2-85, 5-85 and 3-86 were completed
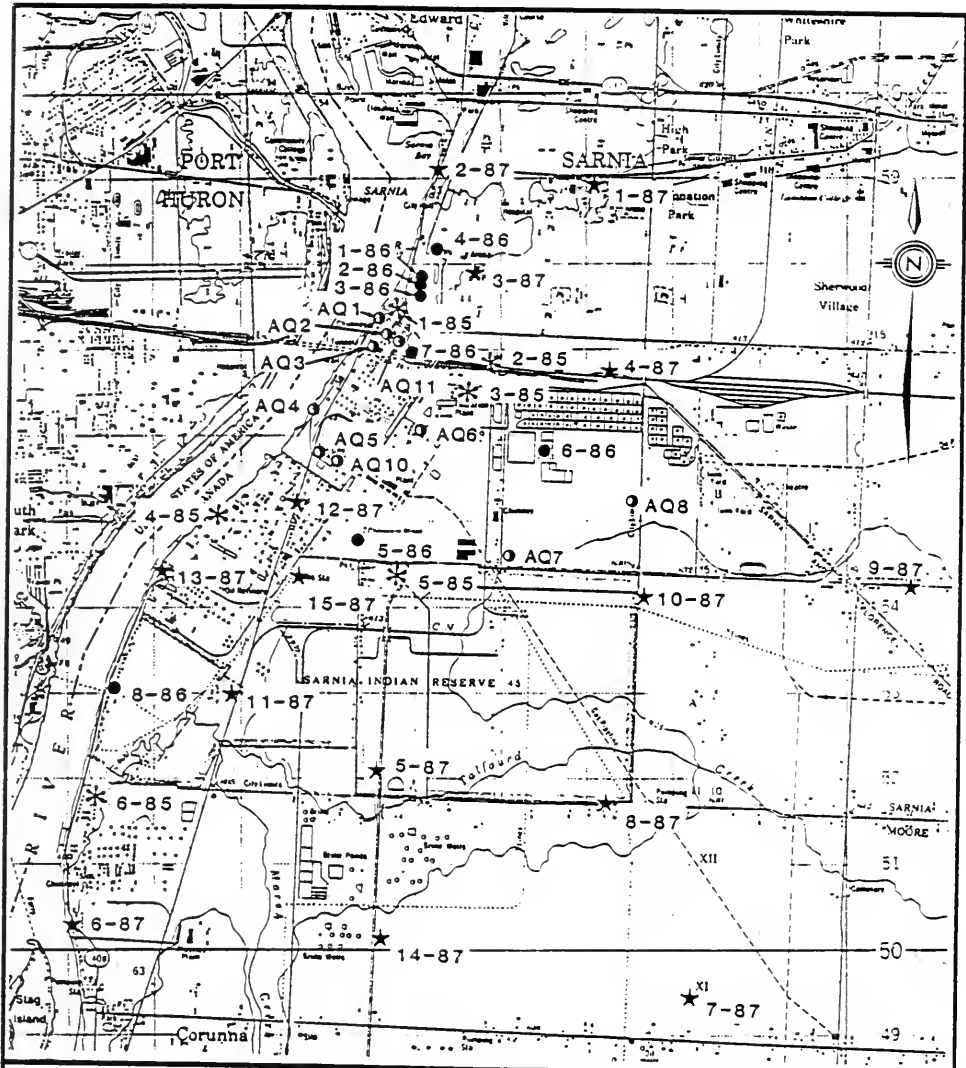
MONITORING WELL NETWORK OF
FRESH WATER AQUIFER

FIGURE 3.1

Table 3.3 Well Installation Details - Depth in m Below Ground Surface

Well Number	Location	Bottom of Hole	Bottom of Screen	Top of Screen	Bottom of Seal	Top of Seal
MOE						
1-85	North end ESSO property	53.9	52.0	50.5	46.0	33.4
2-85	Mitton near Campbell Street	43.9	No Screen	Steel Casing	35.6	0
3-85	St. Andrew St. Sewage Plant	39.9	39.9	33.2	32.0	29.9
4-85	Dow property	39.9	39.9	32.3	29.3	26.8
5-85	Hwy 40 @ Churchill	44.5	No Screen	Steel Casing	36.6	0
6-85	LaSalle Rd.	30.5	30.5	25.5	28.0	23.7
7-85	CIL Plant	41.5	39.0	37.8	28.0	25.9
EC						
1-86	Prince of Wales Park - Deep	54.2	54.2	51.2	46.6	46.0
2-86	Prince of Wales Park - Shallow	10.1	10.1	7.0	3.0	0
3-86	Prince of Wales Park - Pumping	54.9	53.9	47.8	46.6	45.4
4-86	Victoria Park	55.2	54.2	51.2	50.0	48.3
5-86	Huron and Tashmoo	35.0	35.0	32.0	30.5	29.5
6-86	Sludge Lagoons	39.9	39.9	36.9	34.7	31.7
7-86	CN Tunnel	44.2	43.3	40.2	39.0	37.7
8-86	Hydro Tower	36.0	35.7	32.6	30.5	29.5

Table 3.3 Well Installation Details - Depth in m Below Ground Surface (cont'd)

Well Number	Location	Bottom of Hole	Bottom of Screen	Top of Screen	Bottom of Seal	Top of Seal
MOE						
1-87	Germain Park	36.8	36.6	33.7	30.8	29.9
2-87	Centennial Park	46.2	45.9	43.0	42.4	42.0
3-87	Talfourd St.	37.2	36.9	34.0	31.5	30.5
4-87	Campbell & Alice	37.3	37.0	34.2	32.6	31.7
5-87	Hwy. 40 & LaSalle	37.8	37.6	34.7	33.8	33.1
6-87	Guthrie Park	33.7	33.4	30.5	29.4	29.0
7-87	County Rd. 4 @ Side Rd. 19	43.3	43.0	40.1	39.3	38.8
8-87	LaSalle E of Scott	37.2	37.0	34.1	32.3	31.5
9-87	Churchill E of Plank	37.3	37.0	34.1	32.3	31.8
10-87	Air Products	37.9	37.6	34.7	33.1	32.4
11-87	Polymer Rd./S.I.R.	33.0	32.7	29.8	29.6	29.3
12-87	Polysar	71.6	71.3	68.4	64.2	63.9
13-87	Suncor	32.9	32.6	29.7	28.2	27.5
14-87	Hwy. 40 @ Dow Brine	39.7	39.4	36.5	36.2	35.3
15-87	Dow/Churchill & Vidal	60.0	59.7	56.8	54.2	53.7

with 51 mm diameter PVC screen and standpipe. Wells 2-85 and 5-85 were completed with steel casing into bedrock and are water level monitoring wells. Groundwater samples for chemical analyses were not collected from these wells. Well 3-86 was a pumping well and was completed with 101 mm diameter PVC screen and standpipe. Well 7-85 completed at the CIL plant near Courtright is located south of the study area shown in Figure 3.1. The stratigraphic and instrumentation logs for the 1985, 1986 and 1987 MOE and EC monitoring wells are provided in Appendix D.

Also shown in Figure 3.1 are the ten monitoring wells of Esso Petroleum Canada completed to the Fresh Water Aquifer in 1986 and numbered AQ1 to AQ11. Monitoring well AQ9 is MOE monitoring well 1-85. Stratigraphic and well completion details for the EPC wells are given by GLAL/Esso (1987).

Together the MOE, EC and EPC wells represent a network of 40 monitoring wells in the Sarnia area. The location of these monitoring wells with respect to former industrial waste injection wells to the Detroit River Group of Formations is shown in Figure 3.2. With the exception of the Shell Canada Ltd. disposal wells at least one Fresh Water Aquifer monitoring well is located within 500-600 m of the disposal wells shown in Figure 3.2.

3.2.2   Geology

The geology of the Fresh Water Aquifer in the Sarnia area is described based upon borehole data compiled previously (GTC, 1985; INTERA, 1987a and GLAL/Esso, 1987) and from the fifteen boreholes completed as part of the current study.

The geology of the Fresh Water Aquifer is strongly influenced by the existence of a buried bedrock valley located parallel to and approximately 300-1000 m southeast of the St. Clair River. The bedrock valley extends from northeast of Sarnia to as far south as Corunna and averages 30-35 m depth below surrounding bedrock and 60-70 m depth below ground surface. Figure 3.3 shows the overburden or drift thickness in the Sarnia study area based on data reported
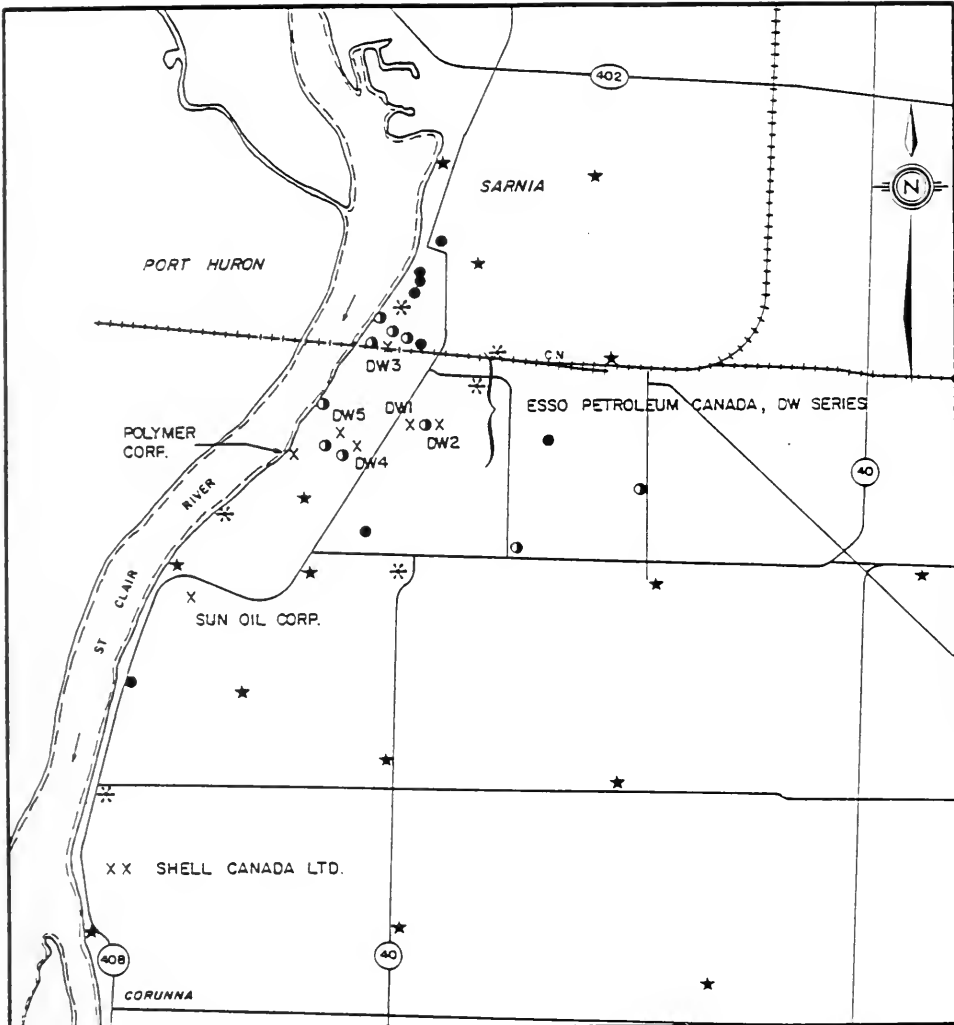
LEGEND

X —— INDUSTRIAL WASTE DISPOSAL WELLS TO DETROIT RIVER
GROUP OF FORMATIONS

Drawn by	Date
Checked by	Date
Revisions	Date

LOCATIONS OF FORMER INDUSTRIAL
WASTE DISPOSAL WELLS TO DETROIT
RIVER GROUP AND FRESH WATER
AQUIFER MONITORING WELLS
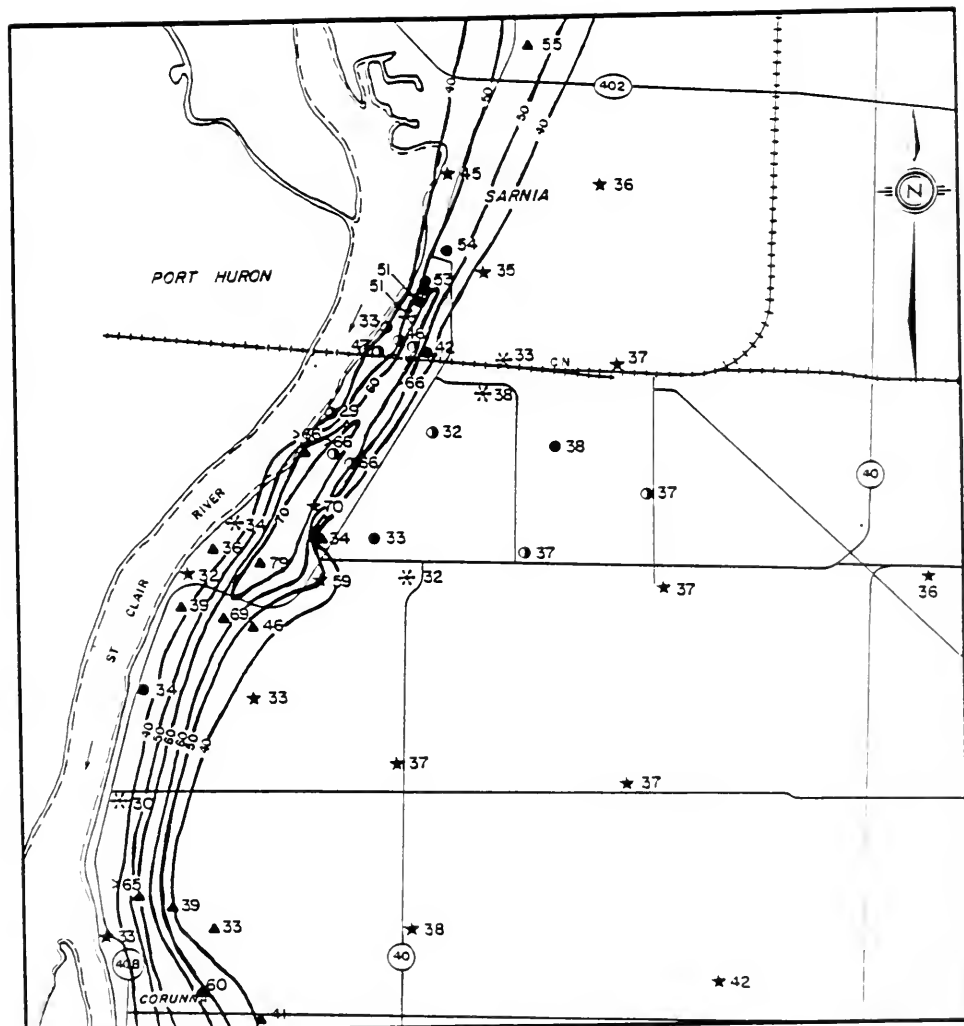
SCALE

FIGURE 3.2

LEGEND

38 — DRIFT THICKNESS IN m

━━60━━ CONTOUR OF DRIFT THICKNESS IN 10m INTERVAL

▲ — DATA REPORTED BY GLAL (1987)

Drawn by	Date	
Checked by	Date	ISOPACH MAP OF DRIFT IN STUDY AREA
Revisions	Date	

SCALE

FIGURE 3.3

by GLAL/Esso (1987) and the 1985, 1986 and 1987 monitoring well installations of MOE and EC. This isopach map shows that the overburden thickness in much of Sarnia and Moore Townships averages 33-40 m and that within the bedrock valley overburden thicknesses of 60-70 m are typical with a maximum thickness of 79 m near the west end of Churchill Road.

Figure 3.4, based on the same sources, shows the structural elevation contours of the top of bedrock in the Sarnia study area. The bedrock valley, as indicated by the overburden isopach map, is deepest and widest near the west end of Churchill Road reaching an elevation of 105 m AMSL and a width of about 1 km. Because the Kettle Point shale averages only 15 m thickness in the Sarnia area, the bedrock within the bedrock valley is the Hamilton Group (i.e., shales and limestones).

Figure 3.4 also gives the location of two geologic cross-sections completed across the bedrock valley in the area of EPC property (Section A-A') and Dow property (Section B-B'). The two geologic sections are shown in Figure 3.5. Geologic section A-A', based on EPC, MOE, and EC well data and CN tunnel data, shows that the Fresh Water Aquifer within the bedrock valley thickens to 15-17 m. Similar thickness of the Fresh Water Aquifer are shown in Section B-B' located about 3 km southwest of Section A-A'.

Within the bedrock valley the Fresh Water Aquifer is not readily identifiable as a thin sand and gravel layer located at the top of bedrock but consists of a complex of clays, silts, and thin sand and gravel layers. Identification of the Fresh Water Aquifer within this sequence in the bedrock valley was further complicated in this current study by the use of a mud rotary drilling technique.

Geophysical logs completed in selected boreholes prior to monitoring well completion provide some additional stratigraphic information. Appendix C summarizes the geophysical logs and interpretation of these logs for boreholes
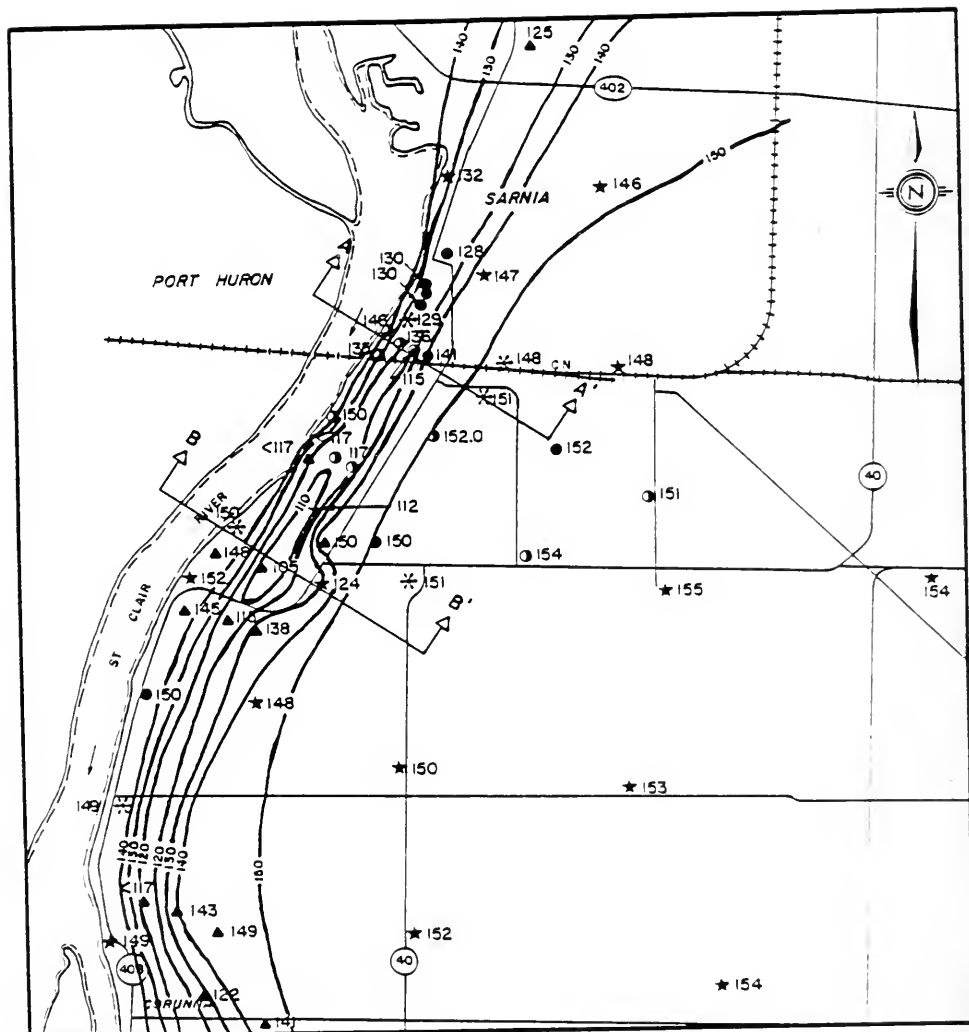
LEGEND

148 — ELEVATION OF BEDROCK SURFACE IN m AMSL

—140— CONTOUR OF BEDROCK SURFACE IN 10m INTERVAL

▲ — DATA REPORTED BY GLAL (1987)

Drawn by	Date
Checked by	Date
Revisions	Date

STRUCTURAL CONTOUR MAP OF BEDROCK SURFACE IN STUDY AREA AND LOCATION OF GEOLOGIC SECTIONS

SCALE
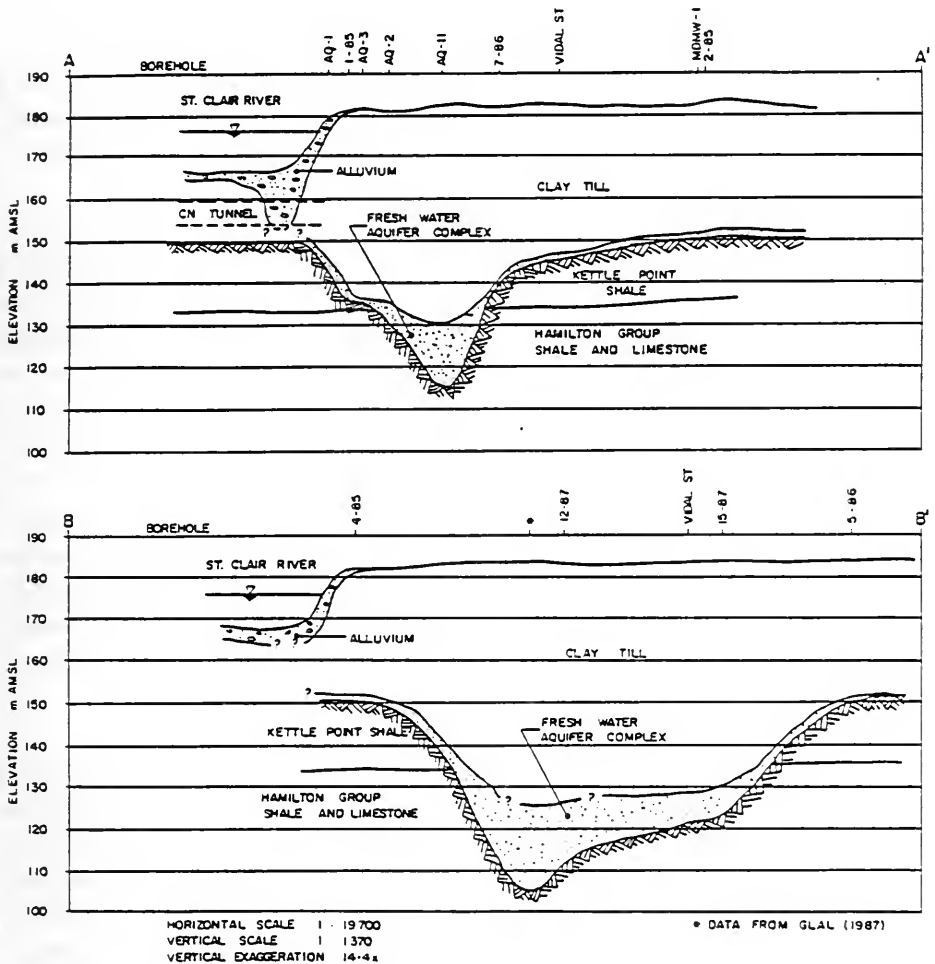
FIGURE 3.4

GEOLOGIC SECTIONS A-A' AND B-B'
THROUGH BEDROCK VALLEY

FIGURE 3.5

1-87, 2-87, 6-87, 12-87 and 14-87. The geophysical logs of boreholes 1-87, 2-87 6-87 and 14-87 drilled outside of the bedrock valley are relatively featureless suggesting very little variation in the nature of the overburden. A general, increase in gamma ray response, reflecting an increase in clay content, is identifiable at depths of 15-20 m in wells 1-87 and 2-87 located in the northern part of the study area and at 0-10 m in wells 6-87 and 14-87 located in the southern part of the study area.

At 17-21 m in well 6-87 there is a decrease in gamma response and an increase in resistivity indicative of a decreasing clay content and increasing sand content. This geophysical feature is interpreted as a thin coarse grained sandy layer within the clay till.

Geophysical logs for 12-87 drilled in the centre of the bedrock valley are generally similar to the four shallower boreholes to a depth of 40 m. Between 40 and 48 m depth there is a decrease in gamma ray response and an increase in resistivity indicative of a decreasing clay content and increasing sand content. Below 48 m depth the geophysical logs and stratigraphic logs indicate a sandy to gravelly clay till which is interpreted to be the Fresh Water Aquifer Complex. A resistivity high and gamma ray low at about 62 m depth is likely a thin sandy and gravel layer within the Aquifer complex.

Throughout most of the Sarnia area, the Fresh Water Aquifer is confined by a 30-40 m thick confining unit of clay till. Within the bedrock valley this thickness increases to 50-55 m. However in some areas below the St. Clair River, close to the Canadian side, the thickness of this confining unit is reduced to as little as three meters as a result of the occurrence of alluvial silt and sand deposits to elevations 153 m AMSL. This occurrence and thickness of alluvium is shown in Section A-A' in the area of the CN tunnel and is also known to exist in the area of the Blue Water Bridge located about 4 km upstream from the tunnel.

3.2.3   Hydraulic Conductivity

Table 3.4 summarizes the results of hydraulic testing of the Fresh Water Aquifer conducted in this study and reported previously by Fleming (1986), INTERA (1987a), and GLAL/Esso (1987).

Slug test results for the 1985 monitoring wells were reported by Fleming (1986). INTERA (1987a) reported slug test results for the 1986 EC monitoring wells and a pump test from the deep pumping well (3-86) in Prince of Wales Park. GLAL/Esso (1987) reported the results of pump tests on three AQ monitoring wells. All other results including testing of 1987 wells, withdrawal and recovery testing of wells and a pump test from 3-86 were determined as part of the current study.

The results of slug testing of the 1987 monitoring wells are given in Appendix E1 in the form of normalized decay plots with best visually fit type curves and summary tabulation of match point values and calculated transmissivities and hydraulic conductivities. Wells 3-87 and 9-87 were slug tested but yielded unanalyzable responses because of significant natural gas production in the wells.

Withdrawal tests were performed in six monitoring wells (6-86, 4-87, 6-87, 10-87, 11-87 and 14-87) to assess the reliability of the slug test results. The data of these six withdrawal tests are summarized in Appendix E2. In general the withdrawal test results are within a factor of two of the slug test results confirming the general reliability of the slug test data.

Recovery tests were performed in four wells (3-85, 5-86, 7-87 and 12-87) to estimate transmissivity and hydraulic conductivity for wells located in low permeability sections of the Fresh Water Aquifer. The data of these tests are summarized in Appendix E3 and calculated hydraulic conductivities ranged from 1×10^{-11} to 1×10^{-9} m/s.

Table 3.4 Summary of Hydraulic Tests, Sarnia Fresh Water Aquifer

Well	Location	Number & Type of Hydraulic Tests	Transmissivity T $m^2 \cdot s^{-1}$	Hydraulic Conductivity K^* $m \cdot s^{-1}$
MOE				
1-85	ESSO	5-Slug	1×10^{-4}	5×10^{-5}
2-85	Mitton St. near Campbell	1-Slug	5×10^{-6}	3×10^{-6}
3-85	Sewage Plant	1-Slug	9×10^{-11}	4×10^{-11}
		1-Recovery	3×10^{-11}	1×10^{-11}
4-85	Staffhouse	6-Slug	2×10^{-5}	8×10^{-6}
5-85	Hwy. 40 @ Churchill	4-Slug	4×10^{-4}	2×10^{-4}
6-85	LaSalle Rd.	6-Slug	6×10^{-6}	3×10^{-6}
7-85	CIL Plant	2-Slug	8×10^{-8}	4×10^{-8}
EC				
1-86	POW Park - Deep	4-Slug	2×10^{-5}	1×10^{-5}
2-86	POW Park - Shallow	2-Slug	2×10^{-7}	1×10^{-7}
3-86	POW Park - Pumping	2-Pump	4×10^{-3}	2×10^{-3}
4-86	Victoria Park	3-Slug	3×10^{-5}	1×10^{-5}
5-86	Huron and Tashmoo	1-Slug	4×10^{-6}	2×10^{-6}
		1-Recovery	2×10^{-9}	1×10^{-9}
6-86	Sludge Lagoons	3-Slug	4×10^{-5}	2×10^{-5}
		1-Withdrawal	4×10^{-5}	2×10^{-5}
7-86	CN Tunnel	3-Slug	2×10^{-5}	1×10^{-5}
8-86	Hydro Tower	3-Slug	6×10^{-5}	3×10^{-5}
MOE				
1-87	Germain Park	4-Slug	2×10^{-5}	1×10^{-5}
2-87	Centennial Park	3-Slug	4×10^{-5}	2×10^{-5}
3-87	Talfourd St.	Gas Producer	$- -$	$- -$
4-87	Campbell & Alice	3-Slug	4×10^{-4}	2×10^{-4}
		1-Withdrawal	4×10^{-4}	2×10^{-4}
5-87	Hwy. 40 & LaSalle	4-Slug	4×10^{-5}	2×10^{-5}
6-87	Guthrie Park	4-Slug	4×10^{-5}	2×10^{-5}
		1-Withdrawal	5×10^{-5}	2×10^{-5}
7-87	County Rd. 4. @ Side Rd. 19	1-Recovery	2×10^{-9}	1×10^{-9}
8-87	LaSalle E of Scott	1-Slug	1×10^{-5}	6×10^{-6}
9-87	Churchill E of Plank	1-Slug	3×10^{-6}	2×10^{-6}

Table 3.4   Summary of Hydraulic Tests, Sarnia Fresh Water Aquifer (cont'd)

Well	Location	Number & Type of Hydraulic Tests	Transmissivity T $m^2 \cdot s^{-1}$	Hydraulic Conductivity K^* $m \cdot s^{-1}$
10-87	Air Products	4-Slug	7×10^{-5}	4×10^{-5}
		1-Withdrawal	1×10^{-4}	7×10^{-5}
11-87	Polymer Rd./S.I.R.	4-Slug	3×10^{-5}	2×10^{-5}
		1-Withdrawal	4×10^{-5}	2×10^{-5}
12-87	Polysar	1-Recovery	6×10^{-10}	3×10^{-10}
13-87	Suncor	4-Slug	1×10^{-4}	7×10^{-5}
14-87	Hwy. 40 @ Dow Brine	4-Slug	4×10^{-5}	2×10^{-5}
		1-Withdrawal	8×10^{-5}	4×10^{-5}
15-87	Dow/Churchill/& Vidal	4-Slug	6×10^{-5}	3×10^{-5}
EPC**				
AQ3	North of CN Tunnel	1-Pump	3×10^{-5}	2×10^{-5}
AQ8	Indian Road	1-Pump	2×10^{-5}	8×10^{-6}
AQ11	Area 1 Christina St.	1-Pump	2×10^{-5}	1×10^{-5}

* Assuming formation thickness of 2 m

** Data reported by GLAL/Esso (1987)

Wells 3-85, 7-87 and 12-87 have very low hydraulic conductivity of less than 2×10^{-9} m/s. These wells also have high pH water indicative of localized failure of the bentonite seal and infiltration of grout into the sand pack. These wells are therefore of limited use as monitoring wells for either hydraulic head measurement or water sampling.

A twelve hour pump test was performed on the pumping well 3-86 located in Prince of Wales Park. The well was pumped at a rate of 560 L/min and drawdown and recovery response was monitored in wells 1-85, 1-86, 3-86, 4-86, 7-86, 2-87 and 3-87 and EPC wells AQ1, AQ2, AQ3, and AQ11. The layout of the pumping and monitoring wells and the bedrock valley are shown in Figure 3.6. The drawdown and recovery responses of these wells are tabulated and plotted with best visually fit type curves of Theis (1935) in Appendix E4. The hydraulic properties of transmissivity, storativity and hydraulic conductivity, determined from this pump test are listed in Table 3.5. The pump tests indicate that the Fresh Water Aquifer in the bedrock valley between Victoria Park and the CN Tunnel is characterized by very high hydraulic conductivity averaging 3×10^{-3} m/s. Reduced permeability boundary effects were observed during the pump test and may reflect the sides of the bedrock valley. Monitoring wells located near the edge or outside of the bedrock valley showed no response (e.g., 2-87, 3-87) or minor response (e.g., AQ1, 7-86) during the test. The geometric mean of all hydraulic conductivity estimates on wells located within the bedrock valley is 1×10^{-4} m/s. This mean was determined from both pump test and slug test data.

Outside of the bedrock valley, the Fresh Water Aquifer is patchy with a transmissivity range of 3×10^{-11} to 4×10^{-4} m^2/s. Where present the Aquifer is relatively permeable and in other locations the low transmissivity of the Aquifer is indicative of the overlying clay till and unfractured shale bedrock. The geometric mean of all hydraulic conductivity estimates on wells located outside of the bedrock valley is 5×10^{-6} m/s.

LAYOUT OF WELL 3-86 PUMP AND
OBSERVATION WELLS

FIGURE 3.6
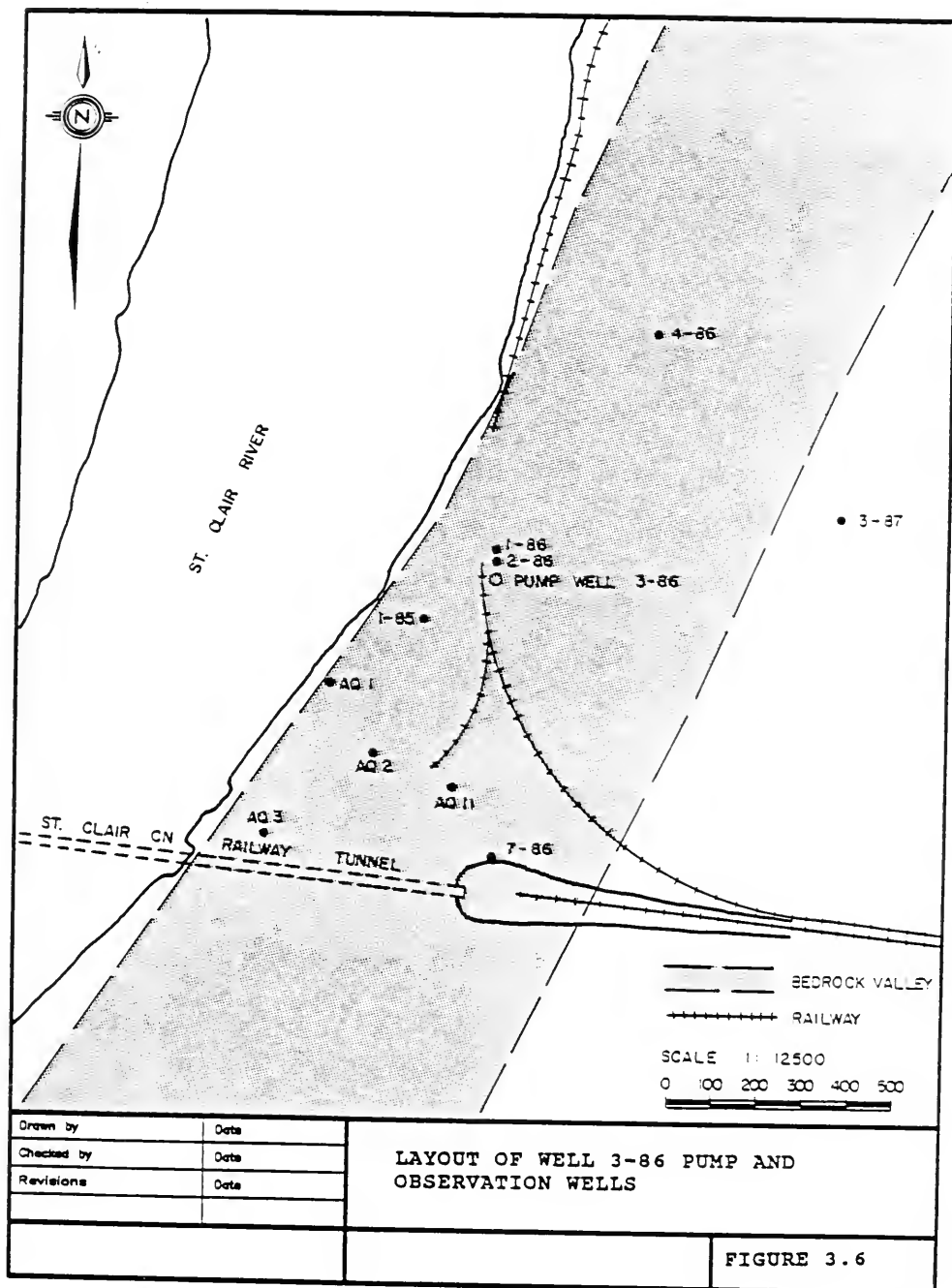
Table 3.5 Summary of Well 3-86 Pump Test Results -
Fresh Water Aquifer

Well	Radial Distance r(m)	Transmissivity T (m^2/s)	Storativity S	Hydraulic* Conductivity K (m/s)
1-85	217	7×10^{-3}	1×10^{-4}	3×10^{-3}
1-86	58	9×10^{-3}	2×10^{-4}	4×10^{-3}
3-86	0	3×10^{-3}	---	2×10^{-3}
4-86	700	5×10^{-3}	7×10^{-5}	2×10^{-3}
7-86	605	2×10^{-2}	2×10^{-4}	1×10^{-2}
AQ1	400	8×10^{-3}	1×10^{-3}	4×10^{-3}
AQ2	470	3×10^{-3}	2×10^{-4}	1×10^{-3}
AQ3	740	7×10^{-3}	1×10^{-4}	3×10^{-3}
AQ11	460	3×10^{-3}	2×10^{-4}	2×10^{-3}
2-87	1600	No response	---	---
3-87	770	No response	---	---

* Determined assuming 2 m formation thickness

3.2.4   Hydraulic Head and Groundwater Flow

Water level data for MOE, EC and EPC monitoring wells are listed in Appendix F. Figure 3.7 shows the water level data of January 19, 1988 for the Fresh Water Aquifer expressed as hydraulic head elevation in m AMSL and contoured to represent a potentiometric surface. Data from wells 7-87 and 12-87 for October, 1987 are not representative of equilibrium conditions due to slow recovery from earlier pumping of the wells. The data for January 19, 1988 are generally representative of equilibrium fluid potentials within the Fresh Water Aquifer. Data from wells 3-85 and 12-87 were not plotted in Figure 3.7 due to the low hydraulic conductivity in the vicinity of the wells and incomplete recovery of the water level from earlier pumping for groundwater sampling.

The potentiometric map shows that groundwater flow within the Fresh Water Aquifer outside of the bedrock valley is generally to the northwest in the direction of the St. Clair River. Hydraulic gradients of 0.0005 to 0.01 are estimated from the potentiometric contours in Figure 3.7 and these gradients generally increase from the southeast to the northwest across the study area toward the bedrock valley. Average hydraulic gradients across the study area to the edge of the bedrock valley (i.e., across potentiometric contours of 183 and 178 m AMSL) are 0.0016.

Using Darcy's Law, an average flow rate through the Fresh Water Aquifer to the edge of the bedrock valley may be calculated assuming an average Aquifer hydraulic conductivity and thickness.   With an average Aquifer hydraulic conductivity of 5×10^{-5} m/s and thickness of 2 m the average flux per unit width through the Aquifer toward the bedrock valley is calculated as 1.6×10^{-3} m^3/s or 0.5 m^3/a. With an average porosity of 0.3 an average fluid velocity of 2.7 $\times$ 10^{-8} m/s or 0.8 m/a is calculated for groundwater flow in the Fresh Water Aquifer toward the bedrock valley.
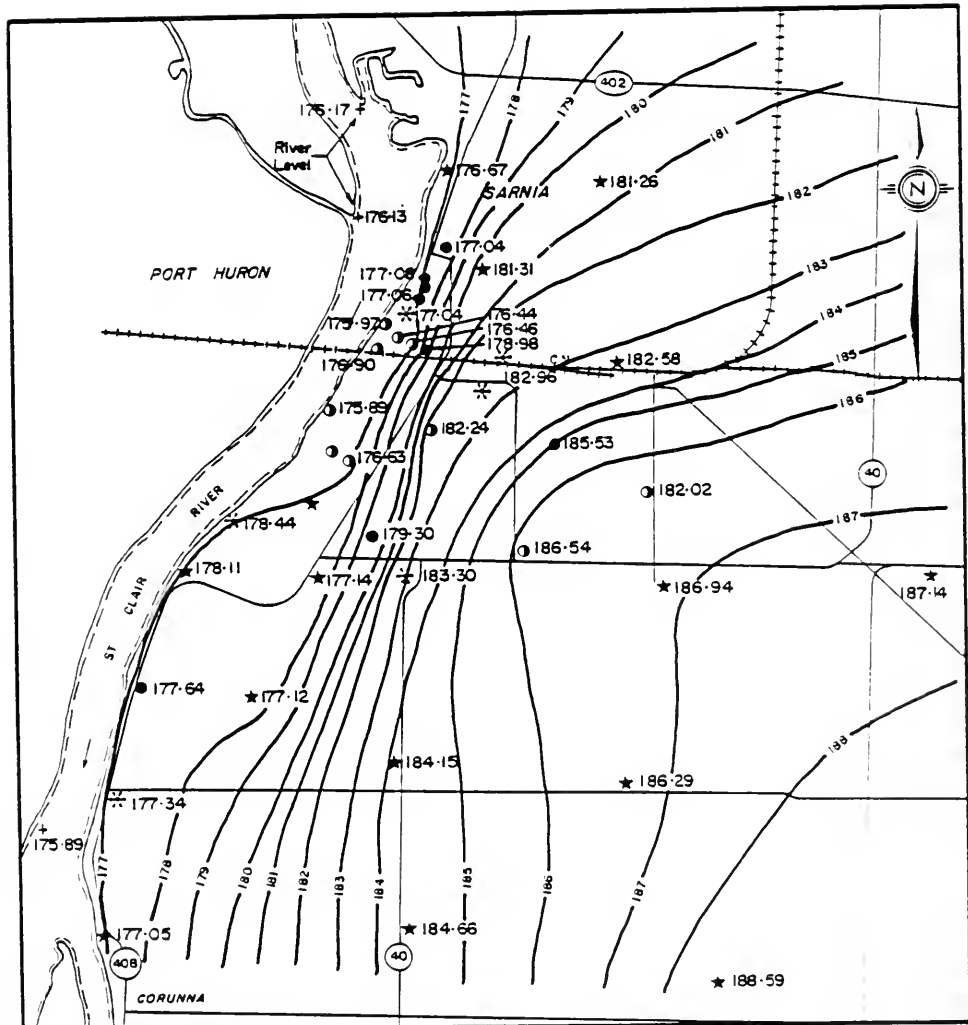
POTENTIOMETRIC SURFACE OF
FRESH WATER AQUIFER
— JANUARY 19, 1988

FIGURE 3.7

Groundwater flow within the bedrock valley and in the vicinity of the St. Clair River is less clear. In the northern end of the bedrock valley fluid levels for the Fresh Water Aquifer, are in places (i.e., wells AQ1 and AQ4), less than the St. Clair River level indicating drainage from the Fresh Water Aquifer to deeper geologic formations. GLAL/Esso (1987) observation of lower fluid potential in the limestone formations underlying the Fresh Water Aquifer in the vicinity of AQ11 supports this interpretation although the reliability of this fluid level measurement is suspect. Other monitoring well data in the north end of the bedrock valley (1-85, 1-86, 3-86, 4-86, 2-87) suggest groundwater flow from the Fresh Water Aquifer to the St. Clair River.

In the southern sections of the bedrock valley fluid levels in the Fresh Water Aquifer (e.g., wells 11-87 and 15-87) are less than fluid levels in the Aquifer adjacent to the river (e.g., wells 4-85, 6-85, 8-86, 13-87) indicating drainage from the Fresh Water Aquifer to the bedrock valley and likely to deeper geologic formations. This interpretation indicates that a local groundwater divide exists between the bedrock valley and the St. Clair River and that groundwater in this area east of the St. Clair River flows both to the St. Clair River and southeastward into the bedrock valley. This local reversal of groundwater flow directions is supported by environmental isotope data discussed in Section 3.2.5.2.

In summary, the groundwater flow in the Fresh Water Aquifer in the study area is generally to the northwest toward the bedrock valley and the St. Clair River. Flow within the bedrock valley is both down to deeper geologic formations and northwestward and up to the St. Clair River. The groundwater flow rate into the bedrock valley from the east is quite low at about 0.5 m^3/a per unit width of Aquifer and it is not possible based on existing information to quantify the relative fractions of this flux which discharge to the St. Clair River or drain to deeper geologic formations.

3.2.5   Groundwater Chemistry

The chemistry of the Fresh Water Aquifer waters are described based on the results of analyses of three sampling events. The water chemistry is described under the following sections:

- Drill Water Tracers;
- Environmental Isotopes;
- Major Ions;
- Metals;
- Total Phenols;
- Volatile Organics;
- Base Neutral Extractables;
- Acid Extractables;
- Organochlorine Pesticides and PCBs.

These analytical results are listed in Appendices G1 to G6. In each Appendix analyses of the Fresh Water Aquifer samples are listed first followed by QA/QC sample analyses.

3.2.5.1   Drill Water Tracers.   The concentrations of drill water tracers in the drill water and development water and the sampled water of the first, second and third sampling events are shown in Table 3.6.   Table 3.6 shows that concentrations of drill water tracers and therefore the levels of drill water contamination are reduced in all wells through development and subsequent sampling rounds.

Table 3.6 shows that water samples collected from the 87 series Fresh Water Aquifer wells in the first sampling round had generally low levels of drill water contamination. However water samples collected from wells 7-87 and 12-87 had 7-10% and 60% respectively of drill water contamination. All other 87 wells sampled in the first round had less than 5% drill water contamination.

In the second sampling round only well 12-87 showed high levels (60%) of drill water contamination.   By the third sampling round, the percentage of drill water present in the well 12-87 sample was reduced to about 37%. All other third round 87 series, well samples contained less than 3% drill water.

Table 3.6   Summary of Tracer Concentrations in Drill Water,
            Development Water and Sampled Water - Fresh Water
            Aquifer

BOREHOLE	TRACER TYPE	DRILL WATER					DEVELOPMENT WATER			1st SAMPLING EVENT	2nd SAMPLING EVENT	3rd SAMPLING EVENT
1-87	I	5.40	2.40				1.70			0.03	0.05	0.04
	Lissamine									-	-	-
2-87	I	1.70	5.40				.06	.25		0.03	0.02	0.01
	Lissamine									-	-	-
3-87	I	4.30					4.00			0.05	0.01	0.01
	Lissamine									-	-	-
4-87	I	5.00	3.50				.90			-	0.08	0.02
	Lissamine	100.00	150.00				16.00	20.00		4.50	1.75	-
5-87	I	2.80	4.30				7.60	2.90		-	0.06	0.02
	Lissamine	90.00	88.00				105.00	23.00	4.00	3.30	0.90	-
6-87	I	3.50	2.90				1.40			0.01	0.03	0.01
	Lissamine	106.00	122.00				23.00	34.00		-	1.0	-
7-87	I	10.00	9.70	2.30	2.00		9.00	2.70	.34	0.70	0.07	0.04
	Lissamine	135.00	110.00	128.00	106.00		104.00	128.00	8.35	7.50	5.10	-
8-87	I	6.50	6.50				.85			-	0.02	0.01
	Lissamine	140.00	142.00				36.00			1.30	0.40	-
9-87	I	7.00	8.20	6.50			2.70	.40		0.06	0.06	0.02
	Lissamine	96.00	118.00	142.00			142.00	10.00		3.30	1.30	-
10-87	I	6.40	6.50	2.30			.06			0.02	0.02	0.02
	Lissamine	126.00	166.00	128.00			20.00	1.30		2.30	1.20	-
11-87	I	4.80					.04	.54	.40	0.35	0.02	0.01
	Lissamine	106.00					22.00	5.25	1.50	1.25	2.75	-
12-87	I	3.30	3.00	2.70	2.30		5.00			-	1.90	1.12
	Lissamine	116.00	172.00	140.00	128.00		48.00			8.00	7.60	-
13-87	I	2.70	2.75	2.80	2.30	2.00	1.00			-	0.12	0.06
	Lissamine	174.00	132.00	142.00	128.00	106.00	10.00			-	-	-
14-87	I	2.40	2.50	3.05	3.00	2.00	2.00			0.32	0.05	0.04
	Lissamine	150.00	146.00	170.00	140.00	106.00	85.00			1.75	0.90	-
15-87	I	2.00	1.55	2.50			.08			0.10	<0.01	<0.01
	Lissamine	118.00	83.00	123.00			20.00			1.25	1.00	-

Note: Iodide (ppm),   Lissamine (ppb)

No Lissamine used in RSHW-1-87 to 3-87

Background Readings for Iodide are <= 0.02 ppm

Background Readings for Lissamine are <= 1.00 ppb

3.2.5.2   Environmental Isotopes. Groundwater samples were collected from all MOE and EC monitoring wells during the first sampling event and analyzed for environmental isotopes ^{18}O, ^{2}H and ^{3}H (tritium). The results of these analyses and other analyses for EPC wells expressed in the ‰ Standard Mean Ocean Water (SMOW) are given in Table 3.7 after Williams (1988) and Sklash et al. (1986). Figure 3.8 summarizes the ^{18}O distribution within the Fresh Water Aquifer and Figure 3.9 is the $\delta^{18}O$ - $\delta^{2}H$ plot for the Fresh Water Aquifer waters.

The ^{18}O contents of precipitation are linearly related to mean annual temperature and therefore ^{18}O contents of groundwater usually reflect the mean annual temperature of the groundwater at the time of infiltration. About 10,000 years ago there was a rapid global warming that increased the $\delta^{18}O$ values of precipitation in southwestern Ontario from -16 to -20 ‰ to values of -8 to -10 ‰ similar to today's precipitation (Desaulniers et al., 1981; Fritz et al., 1985, Edwards and Fritz, 1986).   Desaulniers (1986) showed that the ^{18}O enrichment to present day values can be used to estimate groundwater flow directions in the glacial deposits of southwestern Ontario.   Sklash et al. (1986), Scott (1986), Erdmann (1987) and Williams (1988) have similarly used the ^{18}O data in studies of the Fresh Water Aquifer in Ontario and Michigan. In these studies groundwater is inferred to flow in directions of ^{18}O depletion (i.e., more negative δ values).

The ^{18}O data shown in Figure 3.8 generally indicate groundwater flow from the southeast to the northwest toward St. Clair River. In the vicinity of the bedrock valley in the southern half of the area shown in Figure 3.8 the ^{18}O contents are significantly heavier in ^{18}O and local reversals of groundwater flow have been interpreted in this area by Williams (1988). Possible sources for this ^{18}O enrichment are infiltration of St. Clair River Water ($\delta^{18}O$ = -7.2 ‰) or exfiltration of waters from deeper geologic formations which likely have ^{18}O contents of -10 to 0 ‰ (Dollar et al., 1987).

Table 3.7 Environmental Isotope Analyses* - Fresh Water Aquifer

Well	$\delta^{18}O$ o/oo	$\delta^{2}H$ o/oo	^{3}H TU
1-85	-15.22	-111.6	<6 +/-8
4-85	-14.81	-109.2	<6 +/-8
5-85	-16.3		<6 +/-8
6-85	-13.85		<6 +/-8
1-86	-16.0		<6 +/-8
3-86	-16.43	-120.6	<0.8 +/-8
4-86	-16.55	-121.4	2.1 +/-1
5-86	-15.96	-115.3	7 +/-8
6-86	-16.02		10 +/-8
7-86	-15.9		<0.8+/-0.8
8-86	-14.34		<6 +/-8
1-87	-14.8		<6 +/-8
2-87	-16.86	-121.1	2.9 +/-0.9
3-87	-15.82		<6 +/-8
4-87	-15.4.		<6 +/-8
5-87	-15.93		<6 +/-8
6-87	-13.52		1.2 +/-0.6
7-87**	-15.34		13 +/-8
8-87	-16.03		<6 +/-8
9-87	-15.67		<6 +/-8
10-87	-15.53		9 +/-8
11-87	-14.79		<6 +/-8
12-87**	-10.5	-85.6	
13-87**	-13.2	-99.2	13 +/-8
14-87	-15.7		
15-87	-15.36	-112.8	<6 +/-8
AQ2	-16.3		<6 +/-8
AQ3	-15.4		<6 +/-8
AQ6	-15.0		<6 +/-8
AQ8	-15.4		<6 +/-8
Drill	-7.17 to		75 to 90
Water	7.35	-58	+/-8

* Analyses reported by Williams (1988) and
   Sklash et. al. (1986)

** Suspected drillwater contamination
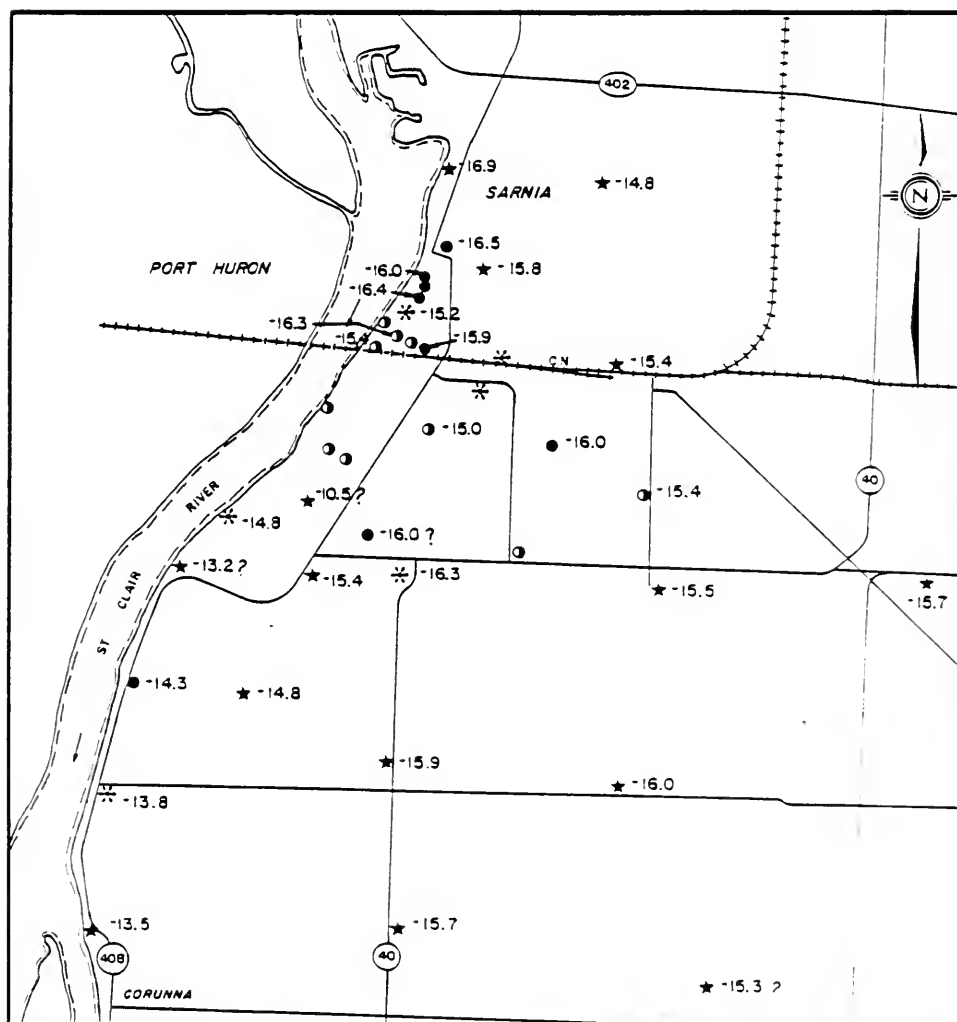
LEGEND

-15.4 —— $\delta^{18}O$ CONCENTRATION IN ‰ SMOW
DATA REPORTED BY SKLASH et al (1986), WILLIAMS (1988)

? —— SUSPECTED DRILL WATER CONTAMINATION

Drawn by	Date
Checked by	Date
Revisions	Date

DISTRIBUTION OF ^{18}O IN FRESH WATER AQUIFER

SCALE
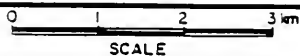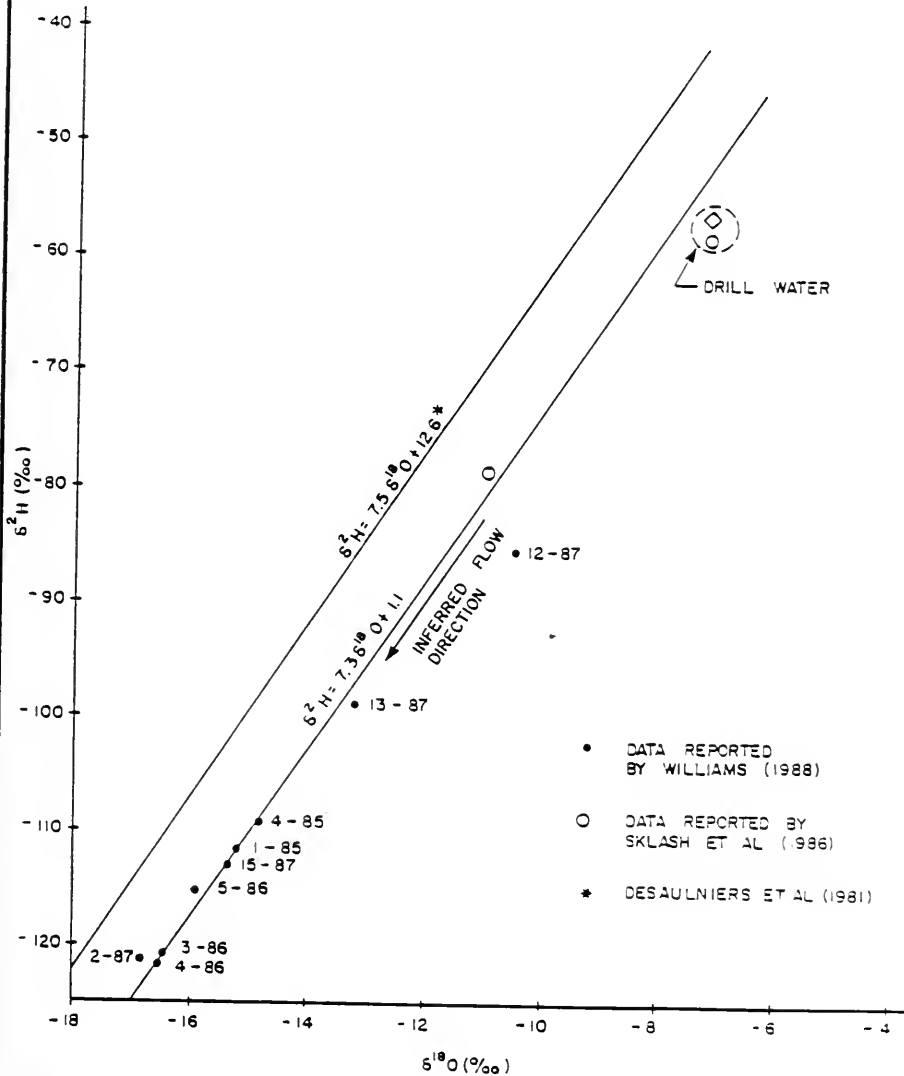
FIGURE 3.8

^{18}O - ^{2}H PLOT OF WATER SAMPLES
- FRESH WATER AQUIFER

FIGURE 3.9

The ^{18}O - ^2H plot (Figure 3.9) shows that water from well 12-87 and to lesser extent well 13-87 contain waters which have been evaporated (i.e., St. Clair River water used for drilling). The other well samples fall on a linear relationship known as the meteoric water line and have not been subject to evaporation. The open circle data point midway along the meteoric water line is a water well sample reported by Sklash et al. (1986) from a domestic well located approximately 30 km east of Sarnia.

The tritium data indicate low levels of drill water contamination in wells 6-86 and 7-87 and 13-87 consistent with available drill water tracer data. The lack of tritium and drill water in those wells between the buried bedrock valley and the St. Clair River in the southern part of the study area (i.e., 6-85, 8-86 and 6-87) suggests recent (post 1955) infiltrated river water is not a source of the ^{18}O enrichment noted earlier for these wells. Enrichment through mixing with other formation waters appears the most reasonable explanation for the measured ^{18}O contents in these wells. Similar mechanisms have been suggested by Long et al. (1988) to explain the range of ^{18}O contents measured in saline near surface water in the east-central Michigan basin adjacent to the St. Clair River and Lake Huron.

3.2.5.3   Major Ions. The major ion chemistry of the Fresh Water Aquifer from three sampling events is given in Appendix G1. The groundwaters are Na-Cl type with Ca-HCO$_3$ as the second most dominate ion group, pH 7.5-8.5 and conductivity 500 - 3300 umhos/cm. Samples from wells 3-85, 7-87 and 12-87 had high pH indicative of grout contamination.

The chloride data for monitoring wells in the Sarnia study area are shown in Figure 3.10. Figure 3.10 is based on analyses completed in this study and on analyses reported by GLAL/Esso (1987) and MOE (1985) and Hatch-Golder (1985). The chloride data shows a general increase in concentration from east to west across the study area ranging from 200 to 1000 mg/L with elevated levels in EPC wells RW-1 (7170 mg/L) and AQ1 (6000 mg/L), CN piezometer 24+10, P-2 (5600 mg/L) and MOE wells 6-85 (1670 mg/L) and 7-85 (1750 mg/L) and 2-87 (1240 mg/L). The high chlorides in RW-1, AQ1 and the CN piezometer are indicative of displaced
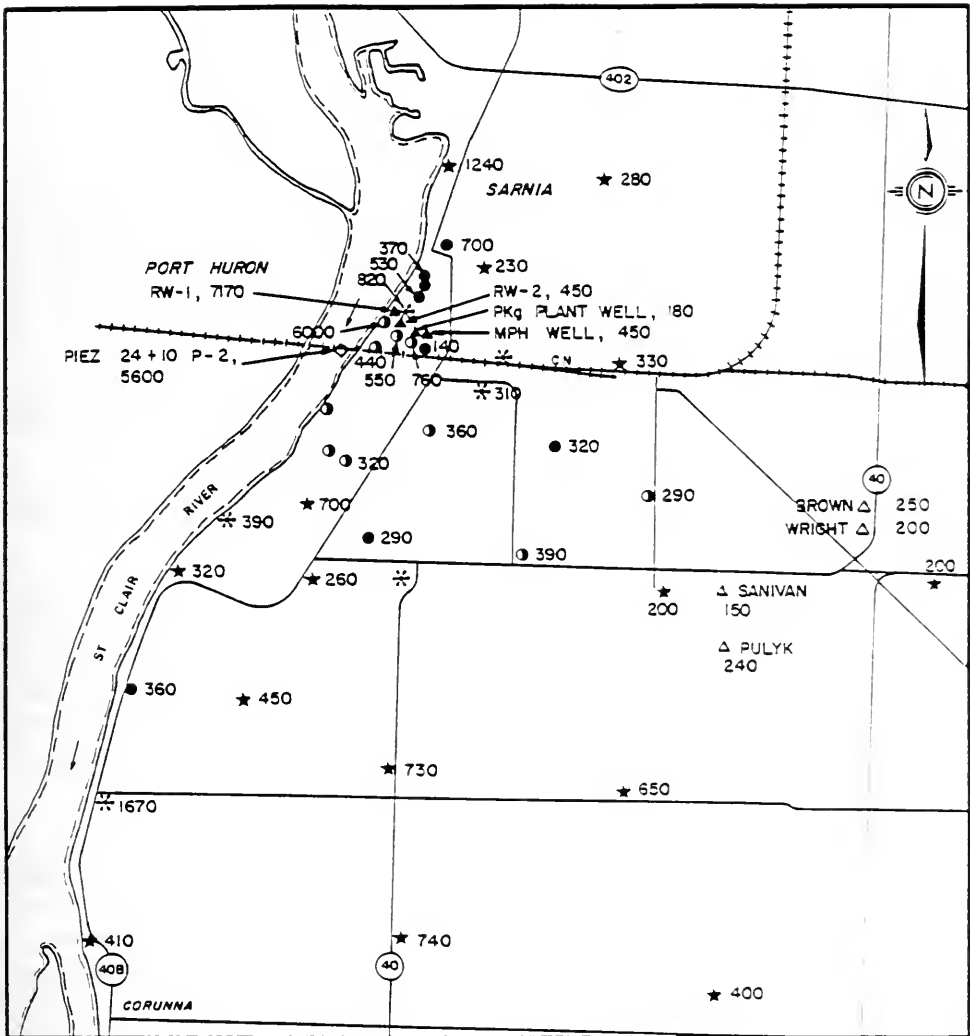
DISTRIBUTION OF CHLORIDE IN FRESH WATER AQUIFER

FIGURE 3.10

deeper formation waters and some industrial waste as elevated phenol levels were also measured at these locations (see Section 3.2.5.5). The slightly elevated chloride levels in wells 6-85, 7-85 and 2-87 suggest some mixing of deeper formation waters at these locations, however, no conclusion regarding upwelling of deeper formation water in these areas, in response to industrial waste injection, can be made based on the available major ion data. The elevated chloride levels in these three wells may reflect regional discharge conditions from deeper formations as postulated by Long et al. (1988) for the Michigan side of the St. Clair River.

The sample from well 4-87 collected from the second sampling round showed higher levels of Cl, Ca, Na and Fe compared to the first and third sampling rounds. The cause of this increase is unclear and the second round analyses are considered anomalous.

3.2.5.4 <u>Metals</u>. Analysis of water samples for metals are listed in Appendix G2. In general the metals analyses indicate low levels of metal concentrations in the Fresh Water Aquifer and no significantly elevated metal concentrations that would be indicative of industrial waste or other contamination. Low level concentrations of barium (5-6 mg/L) and boron (1.2-1.6 mg/L) were measured on waters collected from well 6-85.

3.2.5.5 <u>Phenols</u>. Phenols were a major component of the industrial wastes injected to the Detroit River Group and because they are relatively mobile and have high solubility (e.g., 82,000 mg/L - Verschueren (1983)) in groundwater systems, they are potentially an indicator of industrial waste migration and contamination in the Fresh Water Aquifer. Although phenols naturally occur in formation waters of oil bearing strata at concentrations of 1-4 mg/L (Winters et al., 1976) and possibly 1-10 mg/L (Hunt, 1979), phenols do not naturally occur within the Fresh Water Aquifer. Domestic well sampling performed by MOE for the Fresh Water Aquifer outside of Sarnia (Appendix A2) shows that phenols are not a natural component of these waters.

The results of the phenol analyses performed by the Ontario Ministry of the Environment, London, Ontario as part of the current study are listed in Appendix G1.

This data shows that no significant phenol level was detected in the Fresh Water Aquifer wells as part of the current study. Some low levels of phenol (i.e., $\leq$ 15 ug/L) were detected in selected wells during selected sampling rounds (i.e., 3-85, 4-86, 1-87, 4-87, 7-87, 10-87, 11-87, 12-87, 13-87, 15-87), however these very low levels were not reproducible and are not thought to be significant. Inspection of the QA/QC analyses and duplicate analyses (Appendix G1) indicates that the upper limit for false positive detection of phenols in this study is about 15 ug/L. One well, 3-87 had a result of 22.5 ug/L however below detection limit levels (<1 ug/L) of phenol were found in the other two sampling rounds for the well.

Figure 3.11 shows the distribution of phenol concentrations in the Fresh Water Aquifer based on data collected in this study and from data reported by GLAL/Esso (1987), MOE (1985) and Hatch Golder (1985). Elevated levels of phenol indicative of contamination of the Fresh Water Aquifer were reported on EPC property at wells AQ1 (10,900 ug/L), AQ11 (200 ug/L) and RW-1 (11,000 ug/L) and from the CN tunnel piezometers (24+10 P-2, 150 ug/L; 24+10 G-4, 120 ug/L and 24+70, P-1 520 ug/L). The CN tunnel data are interpreted to represent water quality conditions in the Fresh Water Aquifer although in fact the piezometers are completed within alluvial deposits of the St. Clair River. These phenol data indicate that selected areas of the Fresh Water Aquifer on EPC property near the St. Clair River and near the CN tunnel on the Canadian side are contaminated with phenols.

3.2.5.6 Volatile Organics. Appendix G3 summarizes the volatile organic analyses of the Fresh Water Aquifer completed in this study. These analyses indicate that most of the parameters are below the detection limits of the analytical technique and that the water in the Fresh Water Aquifer from MOE and EC monitoring wells is clean with respect to volatile organics. Some low levels of volatile organics were reported and these results are discussed below.

DISTRIBUTION OF PHENOL IN
FRESH WATER AQUIFER

FIGURE 3.11
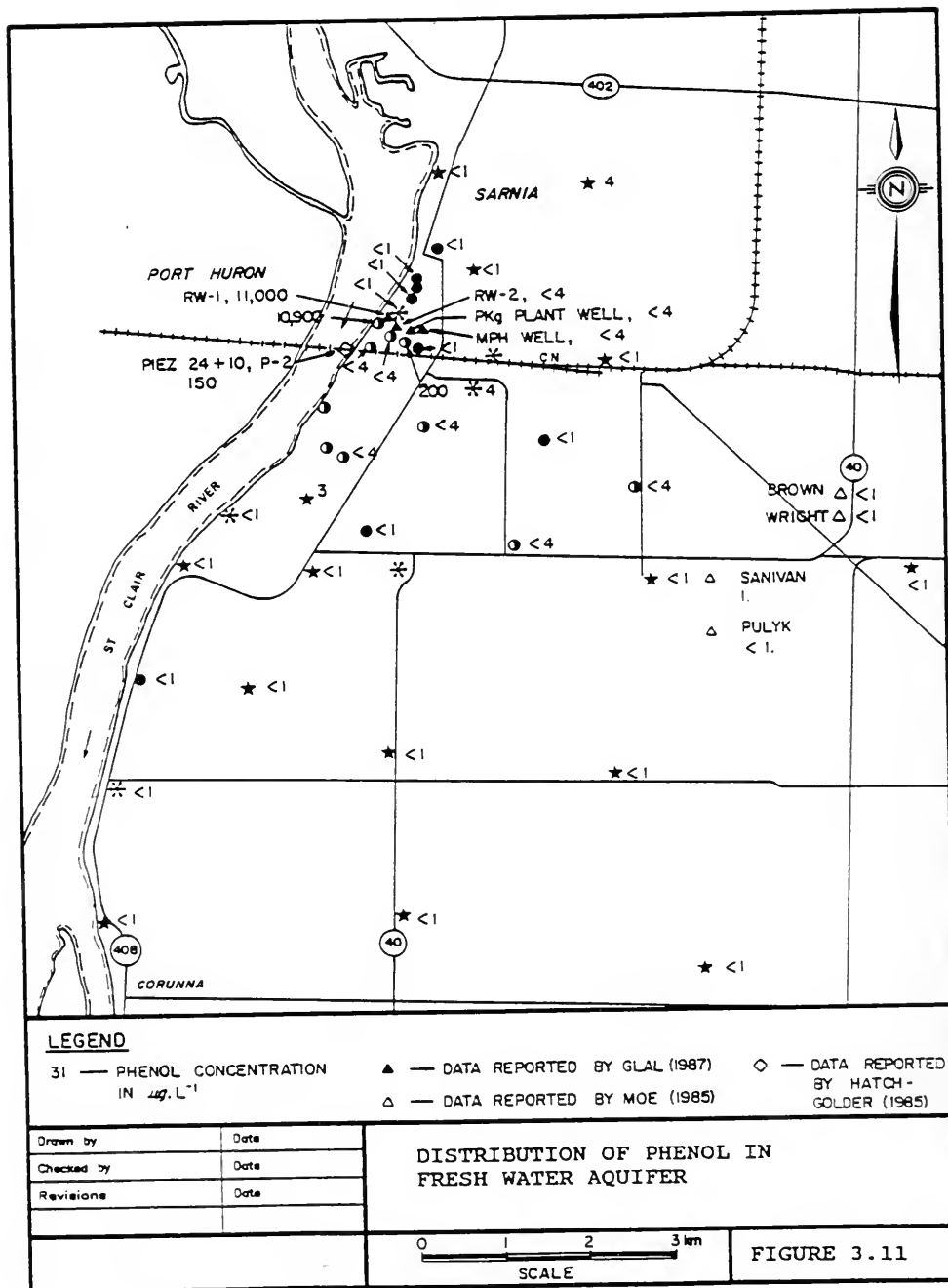
Elevated levels of trichlorofluoromethane, dichloromethane, chloroform and some other compounds were detected in the first sampling round for wells 4-87, 6-87, and 8-87 as well as a drill equipment rinse (sample 87-39-01) and atrip blank. Because these contaminants were not detected in subsequent sampling, the presence of these compounds is likely due to freezer packs or the plastic ice chests used to ship the samples to the laboratory.

Low levels of benzene and toluene were measured during all three sampling rounds for wells 3-85 (up to 12 ug/L) and 4-85 (up to 3.0 ug/L). Low levels of trichlorofluoromethane (up to 8 ug/L) and dichloromethane (up to 70 ug/L) were repeatedly measured for well 12-87. Both wells 3-85 and 12-87 are suspected of being contaminated by cement grout and the low levels measured in these wells may be derived from the grout contamination. The low levels observed for well 4-85 are near the detection limit for the parameters and may not be significant as toluene was detected in a QA/QC sample of a pump blank at 1.9 ug/L.

Low levels of trichloromethane, dichloromethane, chloroform and bromodichloromethane at or below the detection limits (i.e., 0.5-2 ug/L), were randomly reported for the wells sampled in this study. Because of the random nature of these results and the presence of the same compounds in sampling blanks and trip blanks, the compounds are likely derived from the sampling equipment or the analytical laboratory and not from the Fresh Water Aquifer.

3.2.5.7 Base Neutral Extractables. The analytical results of Fresh Water Aquifer samples subject to base neutral extraction and GC/MS analysis are given in Appendix G4. These analyses show that no significant levels of base neutral extractable compounds were found in the analyses of the Fresh Water Aquifer samples collected in this study. Some very low levels of selected base neutral extractable compounds were detected and these are discussed below.

Very low levels of naphthalene (less than 1 ug/L) were detected in four samples collected during the first sampling round and in ten samples collected during the second sampling round. The apparently random occurrence of these low levels of naphthalene combined with the fact that they were not detected in the third sampling round indicates that naphthalene is not present

in the Fresh Water Aquifer samples and was likely introduced during sampling or laboratory analysis.

Phthalates including di-n-butyl phthalate, bis (2-ethylhexyl) phthalate and di-n-octyl phthalate were detected at low levels in field and laboratory blanks, equipment blanks, Sarnia city water, distilled water and frequently in the Fresh Water Aquifer samples. The detected phthalates are likely derived from the sampling equipment (e.g., PVC well completion and sampling pump), Sarnia city water or the analytical laboratory.

3.2.5.8 Acid Extractables. The analysis of samples for acid extractable compounds are listed in Appendix G5. Low levels of phenol at concentrations less than 2.5 ug/L were the only acid extractable compounds detected. Three well samples from the first sampling round and thirteen well samples from the second round had detectable phenol levels. However these low levels of phenol are not thought to be significant as they were not detected in the same well in both the first and second sampling rounds and no phenols were detected in the third sampling round. The source of phenols in the first and second round analyses is likely the analytical laboratory as laboratory reagent blanks showed 6.5 and 43.2 ug/L phenol in the first and second round analyses respectively.

These phenol analysis by GC/MS are consistent with the colourimetric phenol analyses reported in Section 3.2.5.5 and indicate no phenol contamination in the MOE and EC monitoring wells in the Fresh Water Aquifer.

3.2.5.9 Organochlorine Pesticides and PCBs. Appendix G6 contains the analytical results for organochlorine pesticides and PCBs. Inspection of these analyses shows that no significant organochlorine compounds were detected in the Fresh Water Aquifer samples. Some low levels of hexachlorobenzene (up to 0.0061 ug/L) were detected in eighteen of the monitoring wells from the first round of sampling. However, hexachlorobenzene was also found in trip blanks (up to 0.0050 ug/L) and reagent blanks (up to 0.0050 ug/L) in the first sampling round but not detected in the second and third round analyses.

4. INVESTIGATIONS OF DEEP GEOLOGIC FORMATIONS

Investigations of the deep geologic formations in the Sarnia area consisted of comprehensive testing, monitoring and sampling of a 303 m deep borehole completed to the Detroit River Group of Formations. This borehole was drilled on the property of the City of Sarnia Sewage Treatment Plant located at 333 St. Andrew St.

4.1   FIELD METHODS

4.1.1   Health and Safety Program

The general components of the health and safety program followed in completion of the investigations of the deep geologic formations are described in Section 3.1.1. Specific details of the program relevant to the deep geologic formation investigations are provided below.

The potential hazards in the investigations of the deep geologic formations included high pressure gas pockets intersected during drilling and worker exposure to methane, hydrogen sulphide and liquid industrial waste. Safe drilling practices, site monitoring, personal protective equipment and on-site control and handling of waste materials were used to ensure a safe and healthy work environment throughout the investigations of the deep geologic formations.

The "field work area" was defined as a 100 m by 30 m area surrounding the drilling platform and including the decontamination facility and liquid waste storage tanks. As with the Fresh Water Aquifer investigations, no smoking, drinking, eating or ignition of flammable liquids was allowed within the work area. The work area was defined by yellow "hazard" tape and fencing and was located within the fenced area of the Sarnia Sewage Treatment Plant. No one was allowed within the work area without proper safety equipment. Access to the work area was limited and controlled throughout the drilling, testing and sampling programs.

Safe drilling practices including the use of a blow out preventer, standby heavy mud tank, 70 m long gas venting line and a venting line tank were implemented in this project and approved by Ministry of Natural Resources well inspectors. Complete descriptions of the drilling technique are provided in Section 4.1.2.

Monitoring of the work area was performed using a gas detector calibrated for methane, hydrogen sulphide and oxygen contents and an organic vapour meter. Air monitoring was also performed at the top of the well casing and in the discharge area of the gas vent line to detect unsafe working conditions. Unsafe working conditions were defined following guidelines established for the Fresh Water Aquifer investigations (Section 3.1.1).

Personal protective equipment was initially established at a modified level C (low level C) and was elevated to a full level C (i.e., wearing of respirators) on several occasions during drilling through gas pockets at 74 m and 123 m depth and through the disposal zone at about 190 - 210 m. Self contained breathing apparatus were provided on-site throughout the drilling program and were used on one occasion to collect samples of disposal zone fluid discharged through the gas vent line to the vent line storage tank. Continued gas production from intervals at 74 m and 123 m depth required the wearing of respirators during work performed at the well head (i.e., geophysical logging, hydraulic testing) after the completion of the drilling program.

On-site control and handling of drilling return waters was implemented as outlined in Section 4.1.2. Drill return waters from the disposal formation and deeper geologic formations were considered hazardous liquid wastes and stored on site in a series of 4000 L tanks and one large 40,000 L storage tank for later disposal to Tricil (Sarnia) Ltd.

4.1.2   Drilling Program

Prior to the start of the drilling program, approval to drill a 300 m deep borehole to the Detroit River Group was obtained from Ontario Ministry of Natural Resources, the Ontario Ministry of the Environment and the property owner. Site surveys for determining the location of all underground utilities were also performed prior to the start of drilling. The borehole was located on the property of the Sarnia Sewage Treatment Plant in proximity to Esso Petroleum Canada disposal wells (Figure 4.1) and is identified in this report as the MOE deep monitoring well (MDMW-1).

Prior to drilling, drill rods and related drilling equipment were cleaned on the asphalt decontamination pad to ensure that no contaminants were introduced to the borehole from the drilling equipment.

All drill fluid introduced into the deep borehole was tagged with the same tracers (Lissamine FF and Iodide) used during drilling of the Fresh Water Aquifer monitoring wells. Drilling of the deep borehole commenced with triconing of a 155 mm diameter hole through the overburden and 10 m into bedrock to a total depth of 40.8 m below ground surface. This triconing was performed using Sarnia City water as a drilling fluid. Steel casing (HW size - 114 mm outside diameter) was grouted into the hole to hold the blow out preventer. After the cement grout had set, diamond drilling of the cement grout left in the casing and of the underlying bedrock was undertaken.

Diamond drilling of the deep borehole was performed utilizing safe drilling practices and equipment which are schematically illustrated in Figure 4.2.

Drilling was conducted using a light sodium bentonite mud as a drilling fluid and 1400 L of mixed heavy mud was available on standby should significant gas be encountered. The drilling fluid was changed every 3 - 9 m of drilling and temporarily stored in a series of 12 - 4000 L waste water holding tanks. If the
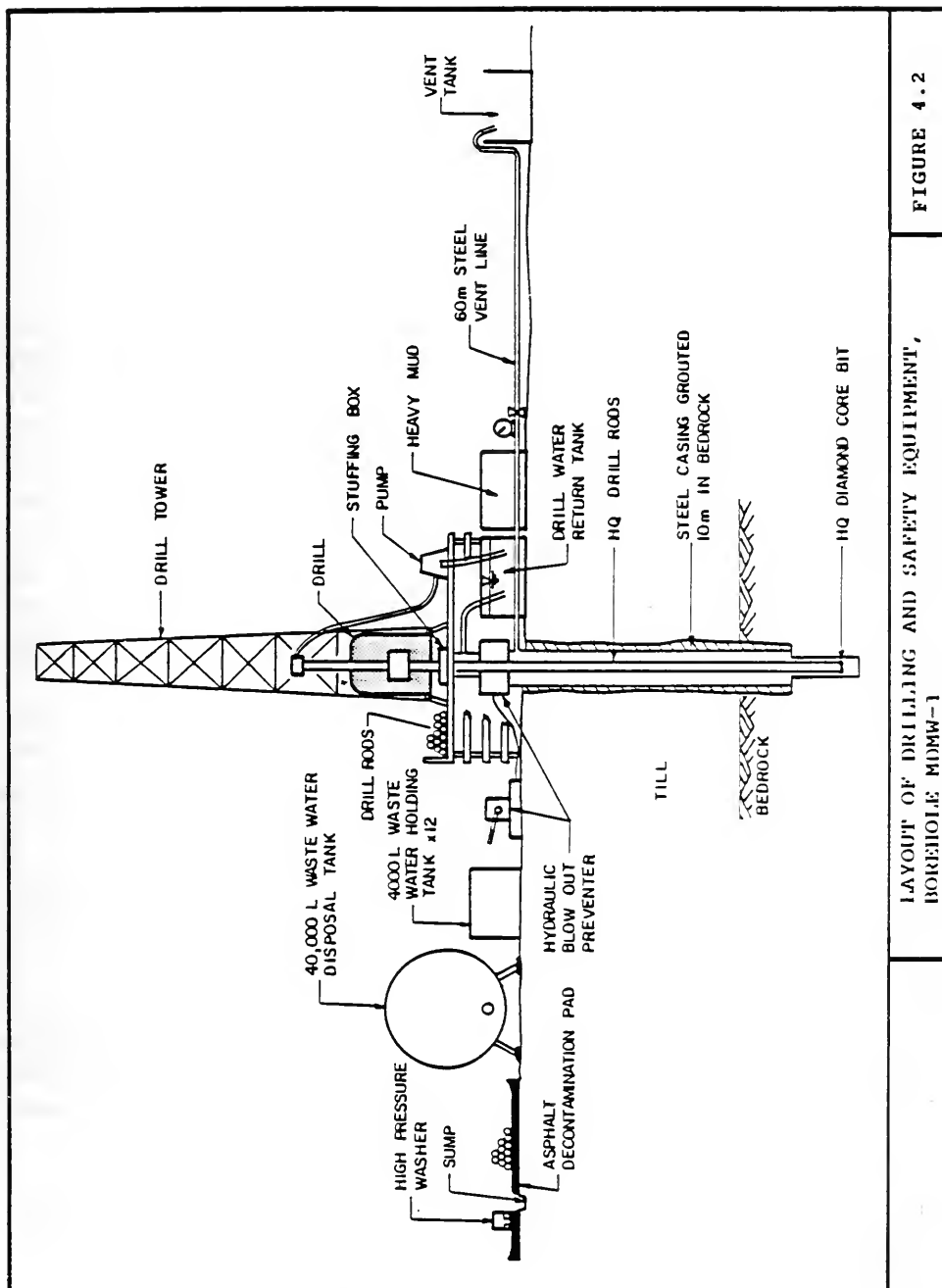
94
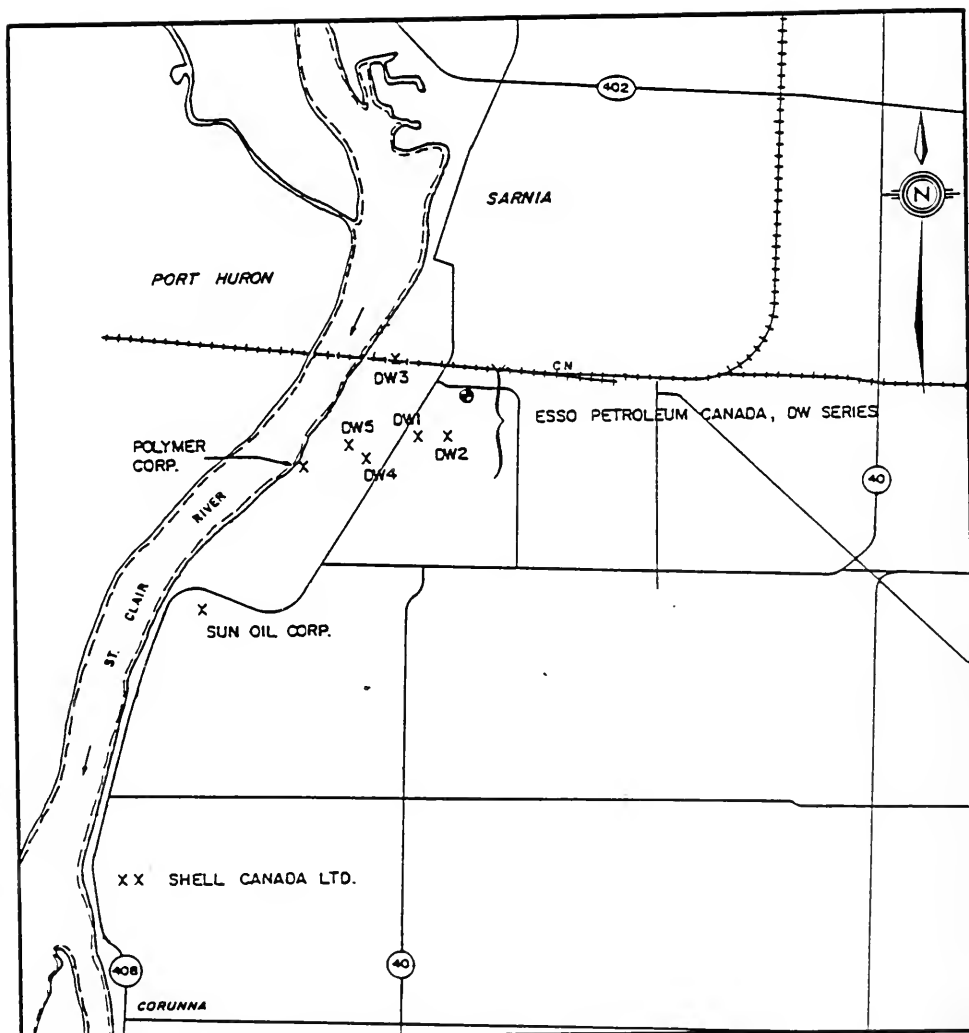
LEGEND

X ——— INDUSTRIAL WASTE DISPOSAL WELLS TO DETROIT RIVER
GROUP OF FORMATIONS

⊕ ——— MOE DEEP MONITORING WELL - MOMW-I

Drawn by	Date
Checked by	Date
Revisions	Date

LOCATION OF MOE DEEP MONITORING
WELL AND INDUSTRIAL WASTE DISPOSAL WELLS

SCALE 0 1 2 3 km

FIGURE 4.1

LAYOUT OF DRILLING AND SAFETY EQUIPMENT, BOREHOLE MDMW-1

FIGURE 4.2

waste drilling fluid was considered contaminated with industrial wastes (based on organic vapour content and selected phenol analyses) the fluid was pumped to the 40,000 L waste water disposal tank. All drilling fluids collected from the disposal formation and below were pumped directly to the waste water disposal tank.   Fluids within the waste water disposal tank were registered as liquid industrial waste and disposed to Tricil (Sarnia) Ltd. by a licensed waste hauler.

A 70 m length of 51 mm diameter steel pipe was used as a vent line to vent gases from the area of drill rig. A 4000 L storage tank was placed below the outlet of the vent line to collect liquid discharged from the vent line. A valve and pressure gauge were placed on the vent line to measure pressure build up in the annular space below the blow out preventer. A stuffing box was placed at floor level of the drilling platform to minimize liquid and gas movement up the outside of the drill rods during drilling.

Drilling was performed using HQ wireline drilling equipment which provided a borehole of 96 mm diameter and a core of 63 mm diameter. Core runs of 3.05 m were used and all retrieved core was lithologically and structurally logged and placed in wooden core boxes. Structural logging of the core included the identification of the location, character and intersection angle of individual fractures and the character of any vuggy or high porosity zones. Occurrences of crude oil and industrial waste in or on the core was also noted.

During the drilling program, drill stem hydraulic tests and groundwater sampling were performed and these activities are described in Sections 4.1.4.1 and 4.1.7.1, respectively.

Following completion of the drilling to 303 m, depth borehole orientation tests (Tro-Pari tests) were performed at 300 m and 152 m to determine the plunge of the borehole. The borehole was flushed with 5600 L of tracer tagged Sarnia city water after this testing.

The drilling program was completed in the period September 16-29, 1987 using one 12 hour shift per day.

4.1.3   Geophysical Logging

        Geophysical logging was performed in borehole MDMW-1 to provide
lithologic and structural information.   The logging was performed by the
Groundwater Research Group, Scarborough Campus, University of Toronto following
the completion of drilling and flushing of the borehole and included the
following logs: 16" normal resistivity, 64" normal resistivity, single point
resistance, natural gamma, gamma-gamma, caliper, fluid resistance, fluid
temperature, and differential fluid temperature.

4.1.4   Hydraulic Testing

        Hydraulic testing for measurement of hydraulic conductivity was
performed during the drilling program (drill stem tests), following drilling in
the open borehole (straddle packer tests) and following Westbay casing
installation (casing withdrawal tests). The following paragraphs describe each
of these testing methods.

4.1.4.1   Drill Stem Tests. Drill stem tests were performed at the end of each
drilling shift. Tests were performed by raising the drill rods a fixed distance
above the bottom of the borehole, removing the wireline corebarrel, lowering a
wireline packer system to the bottom of the rods, inflating the wireline packers
to isolate the test interval, monitoring fluid level to equilibrium values and
monitoring flow rate in response to constant pressure injection.   Figure 4.3
illustrates the Longyear HQ wireline packer system used to perform the drill stem
tests. Flow rate was monitored at surface using an inline cumulative flow meter
with precision of 0.4 L.   Injection pressures were measured at surface and
averaged 100 - 300 kPa. Injection heads were determined from equilibrium fluid
level measurements for the test interval based on water level measurements made
prior to the test and later after casing installation. Injection heads averaged
5 - 40 m and injection periods averaged 30 minutes. Because of the precision
of the flowmeter, the lower testing limit for drill stem injection tests was
about 2×10^{-9} m/s. Eight drill stem injection tests were performed.

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SCHEMATIC OF WIRELINE HQ PACKER SYSTEM USED
TO PERFORM DRILL STEM HYDRAULIC TESTS

FIGURE 4.3

One drill stem withdrawal test (DST-4) was performed by lowering fluid levels within the rods and monitoring fluid level recovery.

4.1.4.2   Straddle-Packer Tests.   Straddle-packer tests were performed using a borehole hydraulic test system developed by Ontario Hydro (Heystee et al., 1987). Figure 4.4 summarizes the components of this testing system which include a borehole straddle-packer probe, trailer-mounted cable reel hoist with 600 m of umbilical cable, surface flow tank system and a data acquisition system.   The straddle packer probe consisted of two steel-reinforced inflatable packers and an instrument pod containing a downhole valve, a pulse piston, three pressure transducers for monitoring pressure within, below and above the test interval and a thermistor for measurement of test interval temperature.   During testing complete records of downhole pressure and temperatures and surface temperatures and flow rates were recorded to facilitate subsequent data analysis and interpretation.   This borehole hydraulic test system has been used to reliably measure the hydraulic conductivity of deep sedimentary rocks with hydraulic conductivity in the range of 1×10^{-14} to 1×10^{-5} m/s.   Test interval lengths of 5.22 m were used in the testing of borehole MDMW-1.

Four types of straddle packer tests were performed in borehole MDMW-1: piston pulse tests; packer pulse tests; below probe packer pulse tests; and injection tests.

Piston pulse tests or packer pulse tests were systematically performed in the borehole every 5.0 from 148 m to 298 m depth to obtain an estimate of the hydraulic conductivity profile within the borehole.   No significant straddle packer testing was performed above 123 m depth because of hazardous buildup of gas below the lower packer and no straddle packers tests were performed between 125 and 148 m depth because of enlargement of the borehole diameter due to drilling operations.   During the piston pulse and packer pulse tests, the decay of a pressure pulse created by displacement of water from either the downhole piston or the inflation of packers was monitored for determination of hydraulic conductivity.   Pulse tests can reliably measure formation hydraulic conductivity in the range 1×10^{-14} to 2×10^{-9} m/s.   Forty-five pulse tests were performed in the deep borehole.
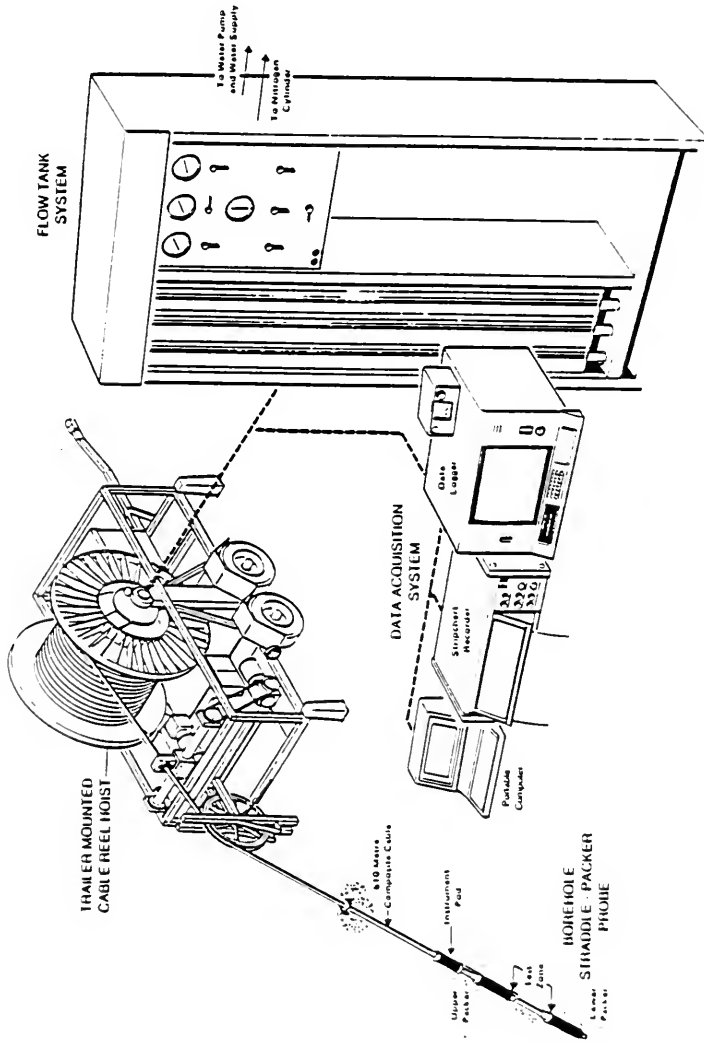
100

SCHEMATIC OF STRADDLE-PACKER HYDRAULIC TEST EQUIPMENT
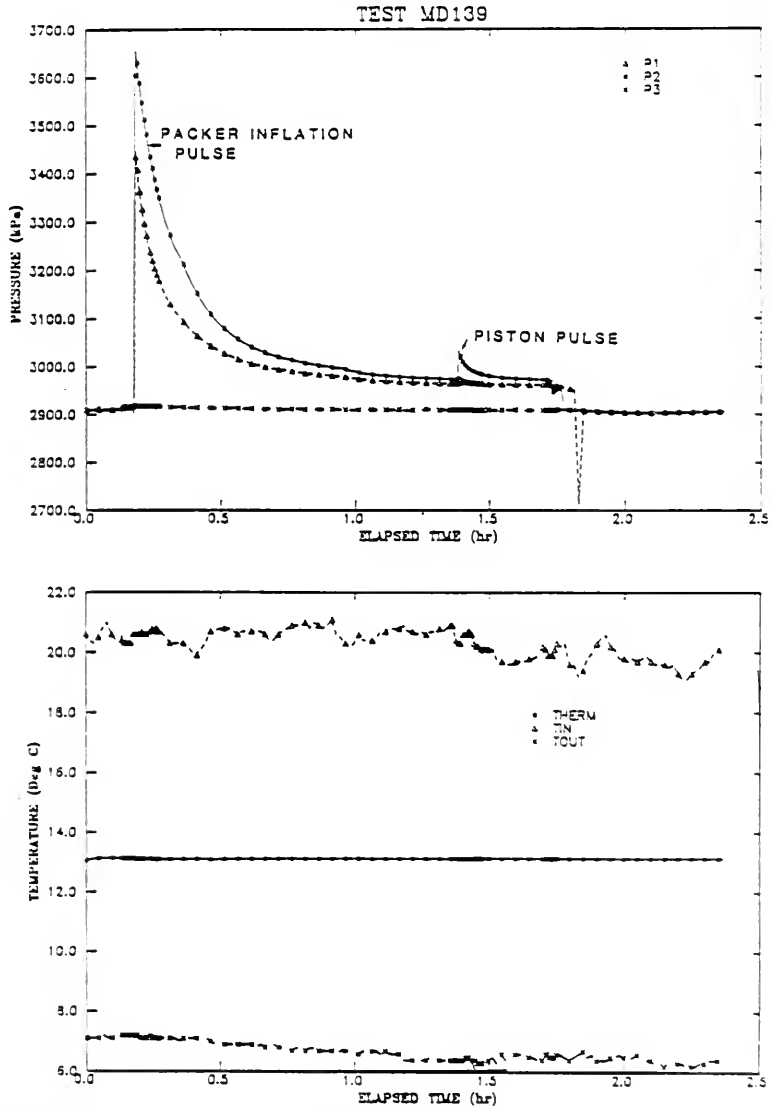
FIGURE 4.4

Because below-probe pressure responses were measurable in the straddle-packer tests, tests performed near the bottom of the borehole created a packer inflation pulse, the decay of which was indicative of the hydraulic conductivity of the formation below the lower packer to the bottom of the borehole. The below-probe pressure response from five tests were analyzed.

Figure 4.5 shows the pressure and temperature sequence plots generated for test MD139 performed at a depth of 293.10-298.32 m. This test illustrates a packer pulse test, a piston pulse test and a below-probe packer pulse test. Figure 4.5 shows the below-probe pressure response (P1), test interval pressure response (P2), above probe pressure response (P3), test interval temperature response (THERM), well head temperature response (TOUT), and instrument trailer temperature response (TIN) throughout test MD139. Similar data were collected for all straddle packer hydraulic tests performed in borehole MDMW-1.

Seven constant pressure injection tests were performed in selected high permeability zones between 183 and 293 m depth. During these tests flow rates were measured at surface and injection pressures were measured within the test interval.

Figure 4.6 shows the pressure and temperature sequence plots for constant pressure injection test MD142 performed at 206.10-211.32 m below ground surface. Test MD142 is an interesting example of the downhole pressure responses to inflation and deflation and shows that the test interval, under open borehole conditions, accepts fluid from below and to lesser extent from above the test interval. This identifies cross formational flow as a significant concern for later groundwater sampling efforts at this depth.

Two pressure buildup (shut-in) tests were also performed at depths of 74.6 - 79.8 m and 123.1 - 128.3 m depth to confirm the location of the gas production zones suspected to exist at these depths. These tests were not analyzed for determination of hydraulic conductivity.

PRESSURE AND TEMPERATURE SEQUENCE
PLOTS OF PULSE HYDRAULIC TEST MD-139
AT 293.1-298.3 M DEPTH

FIGURE 4.5
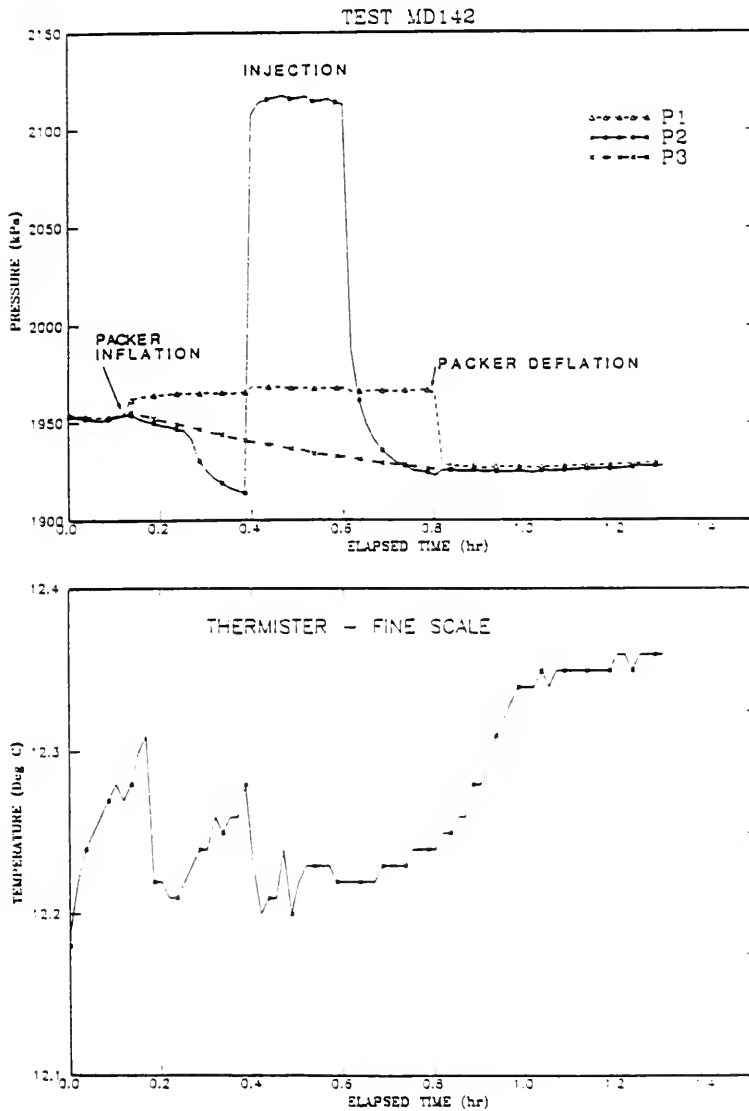
TEST MD142

PRESSURE AND TEMPERATURE SEQUENCE
PLOTS OF INJECTION HYDRAULIC
TEST MD-142 AT 206.1-211.3 M DEPTH

FIGURE 4.6

4.1.4.3 Casing Withdrawal Tests. Hydraulic tests were also performed after installation of Westbay multiple packer casing in the deep borehole. During these tests the packer-isolated test interval was opened to the inside of the plastic casing which had a fluid level reduced to about 20 m below ground surface. Water flowed into the casing and records of water level recovery versus time were used to estimate an approximate steady flow rate and withdrawal head. The withdrawal head was determined from water levels within the casing and from stable formation pressure measurements made prior to opening the interval to the inside of the casing. Because the flow of water to the inside of the casing from the formation was through a restricted opening the withdrawal head in high permeability intervals (i.e., $> 1 \times 10^{-8}$ m/s) was underestimated due to frictional head losses through the restricted opening. Six casing withdrawal tests were performed.

4.1.5 Westbay Casing Installation

Following straddle-packer hydraulic testing, an MP groundwater monitoring system casing was installed in the deep borehole in the period October 21 - 25, 1987. The MP system casing was manufactured by Westbay Instruments Ltd., North Vancouver, Canada and described by Black et al. (1986). The MP system is a modular multiple-level groundwater monitoring device employing a single, closed access tube with valved parts. The valved ports are used to provide access to several different levels of a drill hole in a single well casing. The MP system consists of casing components, which are permanently installed in the borehole, portable pressure measurement and sampling probes and specialized tools. The casing components include casing sections of various lengths, regular couplings, two types of valved port couplings (pressure ports and pumping ports) and packers which seal the annulus between the monitoring zones.

Based upon observations during drilling, recovered core, geophysical logs and the results of hydraulic testing, a monitoring casing system was designed for borehole MDMW-1. The casing design provided eight purgeable monitoring zones accessed by pressure ports and pumping ports for high volume

purging, sampling and pressure monitoring and an additional 19 monitoring zones accessed by pressure ports for pressure monitoring and sampling where high volume purging was not required. The 27 test intervals were isolated by 59 water-inflated packers. The majority of ports were plastic, however, four stainless steel pressure ports were set at 75, 153, 192 and 207 m depth and two stainless steel pumping ports were set at 190.5 and 205.5 m depth. These stainless steel components were set opposite suspected zones of industrial waste, crude oil or high gas pressures.

The Westbay casing was also installed with magnetic locators over each pumping port to aid in determining location within the casing during pressure monitoring and groundwater sampling events. Stainless steel clamps were also added to each coupling and port located between 66 and 148 m depth to provide extra casing strength in suspected gas producing zones.

Prior to casing installation an accumulation of about 120 L of crude oil was purged from the well. This oil accumulated on the top of the water column in the well from the Dundee Formation in the period of geophysical logging and hydraulic testing. During casing installation each joint was hydraulically tested and only one leaking joint was identified. This joint was replaced. Casing installation was supervised by an on-site representative of Westbay Instruments Ltd.

The MP casing installation log and casing completion summary for the deep borehole are given in Appendix H.

4.1.6   Pressure Monitoring

Pressure monitoring of the 27 monitoring intervals in borehole MDMW-1 isolated by the Westbay monitoring casing was performed using an MP pressure probe. The operation of the pressure probe is schematically illustrated in Figure 4.7. The pressure probe measured pressures at the elevation of the pressure measurement port both within the casing and outside of the casing in hydraulic communication with the formation. The pressure probe measured both downhole

Casing

Pressure Probe

Transducer

Location Arm

Valve

MP Measurement Port Coupling

Backing Shoe
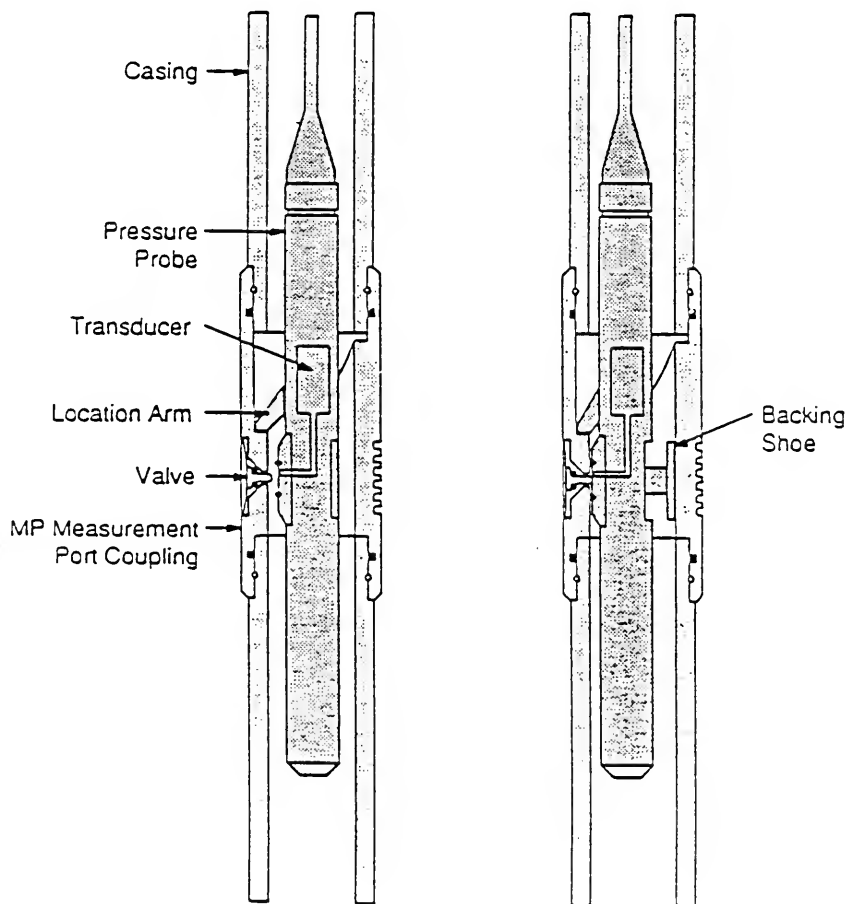
a) Probe Located at Measurement Port Coupling

b) Probe Measuring Fluid Pressure Outside Coupling

Drawn by	Date	
Checked by	Date	OPERATION OF "WESTBAY" PRESSURE PROBE
Revisions	Date	
		FIGURE 4.7

temperature and pressure using an electric pressure and temperature transducer. Pressure profiles of the complete casing installation were performed on October 25, 26, 28 and November 6, 30, 1987 and February 2, March 26 and May 30, 1988. The initial surveys completed following casing installation and packer inflation, monitored the buildup of gas pressure in selected intervals of the borehole. Later pressure surveys were completed prior to groundwater sampling conducted as part of the second, third and fourth monitoring rounds.

4.1.7   Groundwater Sampling

Groundwater sampling of the deep borehole was conducted following protocols established for the Fresh Water Aquifer investigations and modified for the deep borehole studies. Because groundwater sampling was conducted both during drilling and after casing installation slightly different sampling protocols were followed and these are described in the following paragraphs.

The general field sampling requirements for analysis of waters collected from the deep borehole are summarized in Table 4.1. Exceptions to these requirements are also described below.

4.1.7.1   Sampling During Drilling.   During the drilling of the deep borehole groundwater samples were collected from depths of 165.9 m (sample MDMW-1-DWR), 196.3 m (sample MD-1), 229.8-254.2 m (sample MDMLS-1) and 247.5-260.3 m (sample MDMLS-2).

Sample MDMW-1-DWR was collected from the vent (flare) line tank and submitted for analysis of cations, metals and anions to MOE London and Rexdale Laboratories. This sample was thought to be primarily drill water with a small percentage of formation water.

Sample MD-1 was also collected from the vent line tank but contained waste fluids from the disposal horizon at a depth of 196.3 m. Samples were submitted for analyses of cations, anions and phenols by MOE, London, metals by

Table 4.1   Field Sampling Requirements - Deep Borehole

| Analytical Laboratory	Parameters	Sample Containers	Sample Preservation	Sample Filtering
Field Measurement	Lissamine FF, I, fluid density	1-100 mL Plastic	$4^{\circ}C$	Yes
Field Measurement	pH, Conductivity Temperature	----	----	No
Zenon Environmental Inc., Burlington	Cl, F, Br, NO_2, NO_3, PO_4, SO_4, CO_3/HCO_3	1-100 mL Plastic	$4^{\circ}C$	Yes
	Ca, Mg, Na, K, Fe, S and metals	1-100 mL Plastic	Acidified to pH<2 HNO_3 $4^{\circ}C$	Yes
MOE London	Phenols	1-Glass Phenol Bottle	$CuSO_4$ $4^{\circ}C$	Yes
Barringer Magenta Ltd., Rexdale	Purgeable (volatile) Organics	1-40 mL VOA Bottle	$4^{\circ}C$	No
	Acid-Base Neutral Extractables	1-1L Amber Glass	Neutralize to pH 7-10 $4^{\circ}C$	Yes
	Organochlorine Pesticides and PCBs	1-1L Amber Glass	Neutralize to pH6-8 $4^{\circ}C$	Yes
*University of Waterloo	^{18}O, ^{2}H, ^{3}H	1-125 mL Plastic	$4^{\circ}C$	Yes

*Collected once prior to first sampling round

MOE Rexdale, volatile organics, acid and base-neutral extractables and organochlorine compounds by Barringer Magenta, Rexdale and phenols and organics scan (GC/FID) by Enviroclean, London. Sample MD-1 was discharged from the borehole by gas production at 74 and 123 m depth to the vent line tank. The samples consisted of a green and black fluid with non-aqueous phases (both lighter and heavier than water) and a strong organic and H_2S odour. Because of the non-aqueous phases and presence of particulates, the sample was not filtered.

Samples MDMLS-1 and MDMLS-2 were collected from the deep borehole using a Mineral Logging System (MLS) pressurized sampler. This sampling system uses a 2L-volume sample cylinder which is lowered and retrieved from the borehole using a wireline winch. An electric, open-close valve on the sample cylinder ensures fluid samples are collected only from the depth interval of interest. Sample MDMLS-1 was collected from a packer-isolated interval after completion of a drill stem hydraulic test (DST-8). The packer-isolated interval at 229.8-254.2 m was purged of about one interval volume prior to lowering the MLS sampler to the bottom of the rods to collect the sample. Eight litres of sample were collected from a depth of 229 m.

Sample MDMLS-2 was collected in a similar manner to sample MDMLS-1. Prior to sampling, the test interval at 247.5-260.3 m depth was purged of about two interval volumes. MDMLS-1 and 2 samples were characterized as a greenish black fluid with non-aqueous phases and a strong odour of H_2S and organics. Neither sample was filtered. Both samples were submitted for analyses of cations, anions and phenols by MOE, London, metals and cyanide by MOE, Rexdale and volatile organics, acid and base-neutral extractables, and organochlorine compounds by Barringer-Magenta, Rexdale. Analytical methods for these parameters were as described earlier for the Fresh Water Aquifer samples (Section 3.1.5).

4.1.7.2 <u>Sampling After Casing Installation</u>. After installation of the Westbay casing and initial pressure monitoring, interval purging and sampling was undertaken. Interval purging and sampling were performed using the Westbay MP sampler probe. Figure 4.8 illustrates the operation of the sampler probe. Samples are obtained by lowering the sampling probe and sample container to the
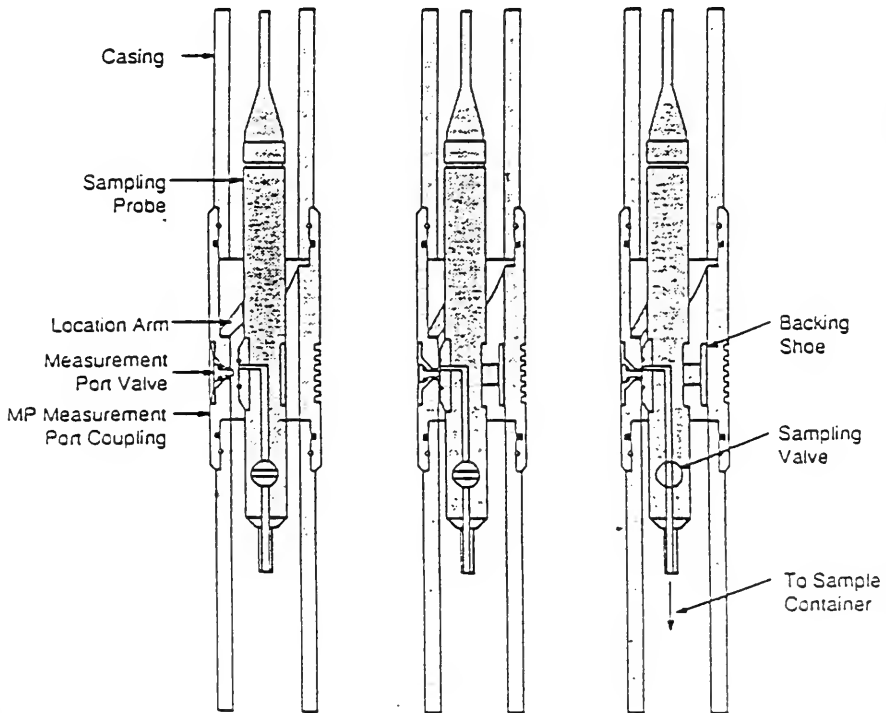
a) Probe Located at Measurement Port Coupling. Sampling Valve Closed.

b) Probe Activated. Sampling Valve Closed.

c) Probe Activated. Sampling Valve Open.

OPERATION OF "WESTBAY" SAMPLER PROBE

FIGURE 4.8

desired measurement port coupling, accessing the formation fluid through the measurement port, opening the sampler valve to the sample container and collecting the sample, closing the sampler valve and retrieving the sampler probe.

Samples for environmental isotope analysis were collected on November 18, 19, 1987 using a 250 mL volume stainless steel sample cylinder and the sampler probe. These samples were collected prior to well purging and may have contained a significant proportion of drill water. Samples were transferred from the stainless steel sample cylinder to the sample bottles at the well.

Only limited purging of the test intervals in the deep borehole was performed prior to sampling for major ion and organic analyses. No purging of interval fluids was conducted from intervals suspected of being located within the disposal zone (i.e., 190 - 220 m depth) because of the high levels of contaminants in these intervals and the desire to minimize contamination of the inside of the Westbay casing and to reduce the potential for cross-contamination of other test intervals. Purging was conducted from intervals at depths of 61.5, 75, 174, 240, 271.5 and 291 m. This purging was accomplished by lowering the fluid level within the casing and allowing fluid to flow from the formation through the sampler probe (which did not have a sample container attached) into the casing. Approximately 1-2 interval volumes were purged from intervals at 240, 271.5 and 292 m and less than one interval volume was purged from intervals at 61.5, 75 and 174 m depth.

Sampling of the deep borehole was conducted from ten intervals centred at depths of 61.5, 75, 123, 180, 192, 207, 228, 240, 271.5 and 291.5 m. Table 4.2 summarizes the depths, sampling frequency and description of these ten intervals.

Four rounds (quarters) of sampling were performed in borehole MDMW-1. Round one was performed November 25-30, 1987; round two - February 1-13, 1988, round three - March 27-30, 1988 and round four May 31-June 3, 1988. Because of difficulty in obtaining sufficient sample volume not all parameters identified in Table 4.2 were analyzed in each sampling event.

Table 4.2 Summary of Sampling - Borehole MIMW-1

Port Depth m BGS	Interval Depth m BGS	Sampling Round	Interval Description	Geologic Formation/Group
61.5	58.2 - 66.1	-,2,3,4	Porous limestone	Ipperwash Formation, Hamilton Group
75.0	70.2 - 79.6	1,2,3,4	High permeability, limestone gas zone, suspected industrial waste	Widder Formation, Hamilton Group
123.0	116.7 - 126.1	1,2,3,4	High permeability limestone, gas zone, suspected industrial waste	Rockport Quarry Formation, Hamilton Group
180.0	179.7 - 183.1	1,2*,-,-	Oil bearing limestone	Dundee Formation
192.0	185.7 - 196.6	1,2,3,4	Disposal horizon, dolomite with anhydrite seams	Lucas Formation, Detroit River Group
207.0	200.7 - 211.6	1,2,3,4	Lower part of disposal horizon	Lucas Formation, Detroit River Group
228.0	224.7 - 231.1	-,-,3,4	High permeability zone, gypsum, anhydrite, dolomite	Lucas Formation, Detroit River Group
240.0	233.7 - 243.1	1,2†,-**,4	Gypsum anhydrite, dolomite	Lucas Formation, Detroit River Group
271.5	265.2 - 274.6	1,2†,-**,-	High permeability zone, dolomite	Lucas Formation, Detroit River Group
291.0	290.7 - 303.0	1,2†,-**,-	High permeability zone, limestone	Amherstburg Formation, Detroit River Group

Notes:
-   Sampling not performed
*   Sampling interval discontinued due to presence of crude oil in sample
**   Sampling of interval not performed due to lodgement of probe near bottom of casing
†   Volatile organic samples only

Sampling of the ten intervals in MDMW-1 for cations, anions, metals, phenols, acid and base-neutral extractables and organochlorine compounds was performed using the sampler probe and 2 to 4, 250 mL stainless steel sample cylinders, attached to the bottom of the sampler probe. Samples collected from the borehole were retrieved to surface under pressure and discharged into 1 L amber glass bottles at the well. Filtering, bottling and acidification of samples were performed in the INTERA field office and laboratory trailer located on the Sarnia Sewage Treatment Plant property. The 250 mL sample cylinders were cleaned between use by rinsing with 10% HCl, detergent and three rinses of distilled water.

Samples for volatile organic analyses were collected during the first and second rounds using the Westbay Volatile Organic Sampler which held a 40 mL VOA bottle. During the third and fourth sampling rounds volatile organic samples were collected using the pressurized stainless steel sample cylinder and transferred to 40 mL VOA bottles.

Samples for total phenol analyses were collected and shipped to MOE, London. MOE, London analyzed the samples from the first, second and third sampling rounds, and selected samples from the fourth sampling round but did not analyze all samples from the fourth sampling round due to high H_2S interference. The remaining analyses were completed by Zenon Environmental Inc., Burlington and were performed as described in Section 3.1.5.

Samples submitted to Zenon Environmental Inc. for anions and metals analyses were analyzed by ion chromatography and inductively coupled argon plasma emission spectrometry.

Samples submitted for volatile organic analyses, acid and base neutral extractables and organochlorine compounds were analyzed by Barringer Magenta Ltd., following the protocol summarized in Section 3.1.5 and described in Appendix B.

Samples for determination of Lissamine FF and Iodide tracer concentrations were only collected during the first two sampling rounds. Due to analytical interferences the reliability of drill water tracer concentrations in the collected samples were suspect. Natural fluorescence of benzene and other aromatic hydrocarbons compromised the use of Lissamine FF as a reliable tracer of drill water in intervals that contained these compounds (i.e., intervals above 210 m depth). Due to salinity variations Ionic Strength Adjuster was added to Iodide samples prior to analyses. To offset sulphide interference to the iodide specific ion electrode, zinc acetate was also added to the samples. Because of the very high concentrations of sulphide present in the majority of samples, the Iodide analytical results are considered suspect. Also because of the high dissolved solids contents of the saline waters and brines located below 210 m depth, natural concentrations of Iodide in these waters are expected to be about 1-2 mg/L.

Fluid densities were determined by weighing known volumes of sample fluid and dividing the fluid weight by the fluid volume. Densities reported in this study were determined at 20°C.

4.1.8   Sampling and Analytical Quality Assurance/Quality Control Program

The sampling and analytical quality assurance, quality control program followed in the deep borehole investigations was the same as the program followed in the Fresh Water Aquifer investigations.

4.2   RESULTS AND INTERPRETATION

4.2.1   Geology

Borehole MDMW-1 was drilled to a depth of 303 m below ground surface. The geologic log of the borehole showing the depth and thickness of the formations intersected and the location of other significant features such as porous/permeable limestone layers and gas production zones is shown in Figure 4.9. Figure 4.9 is based on the lithologic and structural description of the recovered core, geophysical logs of the borehole and previous bedrock geologic

SARNIA   BOREHOLE   MDMW-1

DEPTH (mBGS)	ELEVATION (mAMSL)	LITHOLOGY	CORE DESCRIPTION ROCK TYPE	OTHER	POROUS LIMESTONE LAYERS -ELEVATION THICKNESS (m)	FORMATION	GROUP	PERIOD
0	183·4	OVERBURDEN	grey clay till			GLACIAL TILL		QUATERNARY
	151·7		sand gravel			FRESH WATER		
		KETTLE POINT SHALE	black massive shale	-occ. fissile green layers		KETTLE POINT	PORT LAMBTON	UPPER DEVONIAN
-50	136·0		grey-black limestone & shale fossilifer-ous		129.4 (0.33)			
					123.2 (0.60)	IPPERWASH AND WIDDER (MIDDLE LIME)		
			dark grey calcareous shale & limestone	gas zone at 0.7 MPa	119.0 (1.95)			
					110.0 (1.90)			
				-open fracture	100.5 (0.42) 99.2 (1.16)	HUNGRY HOLLOW	HAMILTON	
-100		HAMILTON GROUP SHALE AND LIMESTONE	dark grey massive clay shale	fissile some pyrite	86.9 (0.20) 79.1 (0.25)	ARKONA		
				-gas odour on core	68.6 (0.30)			
			limestone with shale	-gas zone at 1.3 MPa	60.0 (2.00)	ROCKPORT QUARRY		
			soft dark grey shale	-vuggy, calcareous	54.3 (0.35) 42.4 (0.25)	BELL		
-150	39·6		light grey fine grained limestone oil bearing	-mud seam -stylolites -mud seams -coral fossils open, vugs				MIDDLE DEVONIAN
		DUNDEE LIMESTONE		-fossils		DUNDEE		
	0		light brown sucrosic massive limestone	-occ. dolo- mite seams -open fractures -strong odour				
-200	-4·6		porous light brown dolo- mite & anhy- drite	-high porosity zone -strong odour -sulphur & black bit- umin on fractures -pin hole porosity				
			brown to buff dolomit gypsum & anhydrite					
		LUCAS DOLOMITE	massive buff suc- rosic dolomite	-oil seam -anhydrite gypsum seams		LUCAS	DETROIT RIVER	
-250			buff dolomite & anhydrite	-oil zone -mud seams -occ. breccia zone				
			massive buff dolomite	-shale zone -pin hole porosity -oil stain				
-300 303	-95·7 -119·6	AMHERSTBURG DOLOMITIC LIMESTONE	light grey limestone with shale & dolomite	-mud seams -coral fossils -gypsum infilling -oil stains		AMHERSTBURG		

| GEOLOGIC LOG OF BOREHOLE MDMW-1	FIGURE 4.9

studies in the Sarnia area (Uyeno et al., 1982; GLAL/Esso, 1987). Complete (e.g., 100%) core recovery was obtained during drilling of borehole MDMW-1. No zones of cavernous porosity or lost drill fluid circulation were encountered during the drilling program.

Figure 4.9 shows that borehole MDMW-1 intersected the Kettle Point shale, the Hamilton Group of limestone and shale, the Dundee limestone, the Lucas dolomite and terminated in the Amherstburg dolomitic limestone at 303 m depth. Identification of these formations and in particular individual formations within the Hamilton Group was aided significantly by geophysical logs.

Figure 4.10 summarizes the geophysical logs completed in borehole MDMW-1 and some of the significant features identified from these logs. A complete interpretation of these logs is given in Appendix C. A brief interpretation of these logs in conjunction with the description of the core is provided below.

Borehole MDMW-1 intersected bedrock of the Kettle Point Formation at a depth of 31.7 m. No sand or gravel unit was present at the top of the bedrock. The Kettle Point shale was a 15.7 m thick massive black shale with occasional fissile green layers and pyritized fossils and extended to an elevation of 136.0 m AMSL. Only one open fracture, which was subvertical at a depth of 43 m, was intersected by the borehole in the Kettle Point formation. The organic rich shales of the Kettle Point Formation are readily identifiable on the gamma log as high gamma counts (features C, and D on the log in Figure 4.10) which also influenced the gamma-gamma log (Features B and E).

The contact between the Kettle Point shale and the underlying Ipperwash Formation is demarcated on the geophysical logs at a depth of 47.4 m by the reduction in signal of gamma and gamma-gamma logs and in the core by a change from dark brown organic rich shale to grey calcareous shales. Within the upper Hamilton Group, distinction of the Ipperwash and Widder Shales was difficult and

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FIGURE 4.10

GEOPHYSICAL LOGS COMPLETED IN BOREHOLE MDMW-1
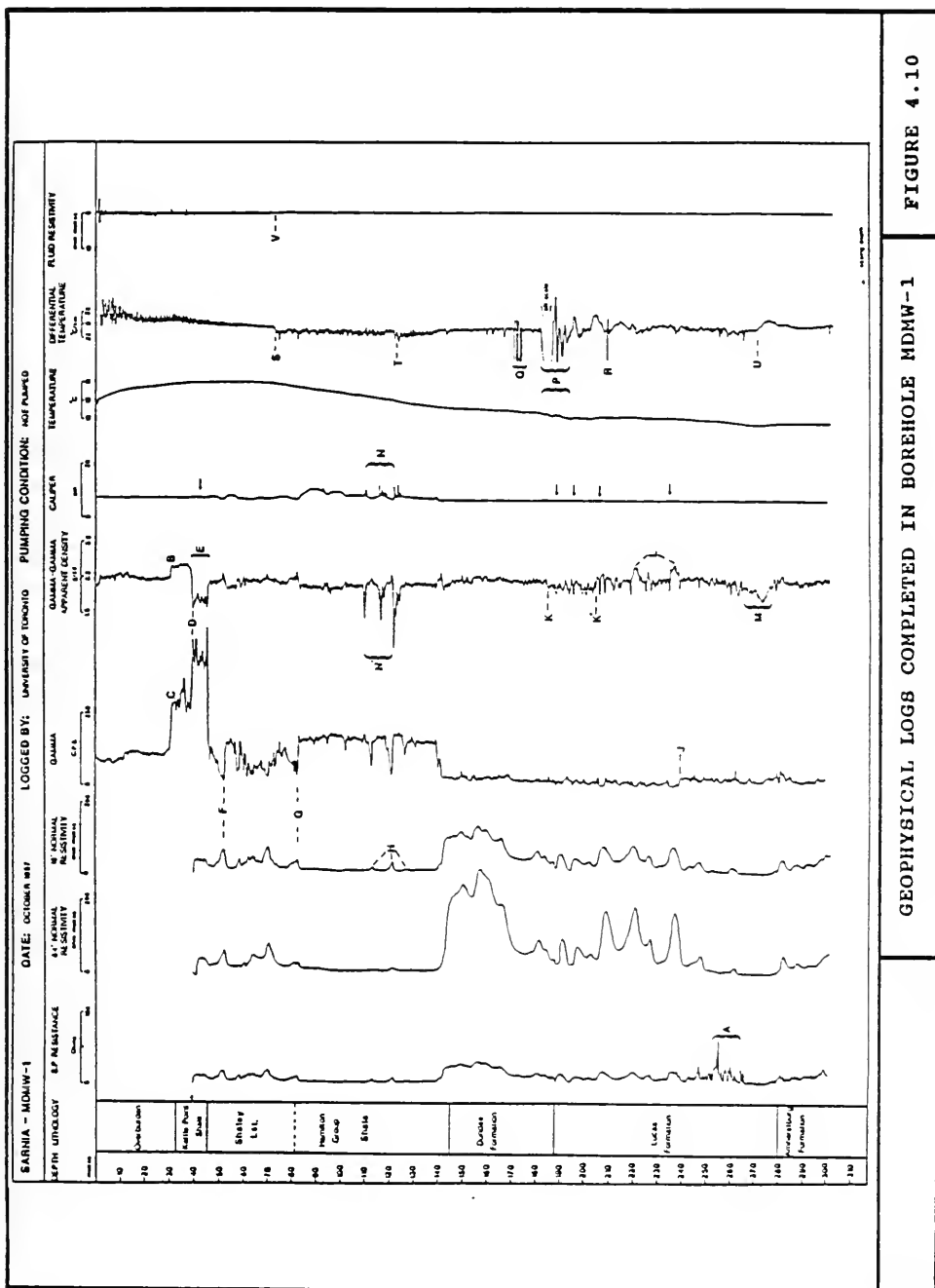
only the lower contact of the Widder Formation with the Hungry Hollow Formation at a depth 83.5 m was reliably identified (feature G on the geophysical logs). However, several significant porous and permeable limestone layers were identified in the core (Figure 4.9) and in the geophysical logs of the Ipperwash and Widder Formations at depths of 54, 65 and 74 m. These carbonate rich horizons are identifiable on the geophysical logs as gamma lows and resistivity highs. The subdued responses on the resistivity logs suggests that the formation fluids in these and other deeper carbonate beds are highly saline.

Significant gas production from the carbonate bed at 74 m depth was observed during drilling. Shut in pressures of 700 kPa were measured at surface on the gas vent line from this limestone layer. A natural open horizontal fracture was also identified at 72 m depth close to the carbonate bed. Features S and V on the differential temperature log and the fluid resistivity log respectively demonstrate this gas production zone at a depth of 74 m.

The Hungry Hollow Formation is readily identifiable as a 1.2 m thick crinoidal bioclastic limestone layer at 84 m depth in both geophysical logs and core logs.

Below the Hungry Hollow Formation (i.e., 84.7 m depth) the borehole intersects about 37 m of dark grey, massive clay shale with three thin limestone layers. This shale unit is readily identifiable on geophysical logs as a resistivity low and gamma high.

From 122 to 124 m depth the borehole intersects a permeable limestone layer of the Rockport Quarry Formation. This marker bed is evident on the geophysical logs as a resistivity high (feature H), a gamma low and a gamma-gamma low (lower N feature). The low density inferred from the gamma-gamma log suggests high porosity and/or gases in the pore space of the Rockport Quarry Formation. During drilling gas production at 1300 kPa pressure was measured from this zone at 123 m depth. This gas production is evident on the differential temperature log as feature T. During drill stem testing (DST-4) over this interval, a greenish black foam with strong H_2S and organic odour was detected

at the top of the drill rods. Based upon similar odours and colours of waste collected from the disposal zone, the observations from drill stem testing suggest industrial waste may be present within the Rockport Quarry Formation at 123 m depth.

Below 123 and to 143.8 m the borehole intersects soft dark grey shale of the Bell Formation.

At 143.8 m the contact with the underlying Dundee Formation was intersected and this boundary is well portrayed on the geophysical logs by a sharp drop in the gamma response and rapid increase in resistivity. The relatively high resistivity values are interpreted as low percentage water saturation with the remaining pore space occupied by hydrocarbons. Core observations indicate the Dundee Formation as predominately oil bearing between 143.8 and 168 m depth. The lower sections of the Dundee limestone are more massive grading to sucrosic texture and increasing dolomite content with depth. Strong organic (phenolic) odours were observed on the core retrieved from the lower sections of Dundee Formation at depths of 185-187 m.

At 187 m depth the contact between the Dundee Formation and the Lucas Formation was intersected. The upper sections of the Lucas dolomite from 187 - 203 m are a buff brown dolomite with pinhole porosity, occasional vugs and anhydrite layers. Subsequent groundwater sampling identified this zone as the zone of residual contamination or the preferred disposal horizon in the Lucas Formation. Bitumin and elemental sulfur were observed as fracture infillings in this zone. The differential temperature log at this depth (feature P) is extremely agitated reflecting the significant flow of borehole fluids from lower sections of the borehole to the disposal horizon.

From 203 to 280 m, borehole MDMW-1 intersects Lucas dolomite with varying textures, porosities and percentages of anhydrite and gypsum. Bituminous coatings on fractures and occasional thin oil seams were observed on the core over this depth range. Low density, high porosity zones (feature M on the gamma-gamma logs) and the differential temperature feature U, both at 270 - 276 m depth

indicate flow of fluid from the formation at this depth into the borehole. This fluid likely flows out of borehole at the disposal horizon at 187-203 m depth.

From 280 to 303 m the borehole intersects dolomitic limestone of the Amherstburg Formation.

Borehole orientation surveys completed at the end of drilling at 300 m and 152 m depth both showed that the borehole was vertical with a plunge of 90°.

4.2.2   Hydraulic Conductivity

The test data and analyses of all hydraulic tests performed on borehole MDMW-1 are given in Appendix I. These test results and hydraulic tests in the Kettle Point shale and upper Hamilton Group limestone reported by GLAL/Esso (1987) are plotted in Figure 4.11 in a depth profile with the geologic log. The hydraulic conductivity data in Figure 4.11 are in m/s and are plotted on a log scale where -10 is equal to 1×10^{-10} m/s and -8 is equal to 1×10^{-8} m/s etc. The results of over sixty tests are plotted in Figure 4.11 and because different tests have different reliabilities, an interpreted profile of the hydraulic conductivity distribution in borehole MDMW-1 is also shown. The interpreted profile is the best estimate of the distribution of horizontal hydraulic conductivity in the borehole.

Figure 4.11 shows the hydraulic conductivity of the overlying till as 1×10^{-10} m/s and the Fresh Water Aquifer as 1×10^{-5} m/s based on data reported in Sections 2.2 and 3.2.3.

The only estimate of hydraulic conductivity of the Kettle Point shale is from GLAL/Esso (1987) at 1×10^{-10} m/s based on packer testing. As discussed earlier this hydraulic conductivity likely reflects the conductivity resulting from fractures and because an open subvertical fracture was logged at 43 m in the borehole the result is likely representative of conditions in borehole MDMW-1.

HYDRAULIC TEST RESULTS AND INTERPRETED PROFILE - MDMW-1

FIGURE 4.11
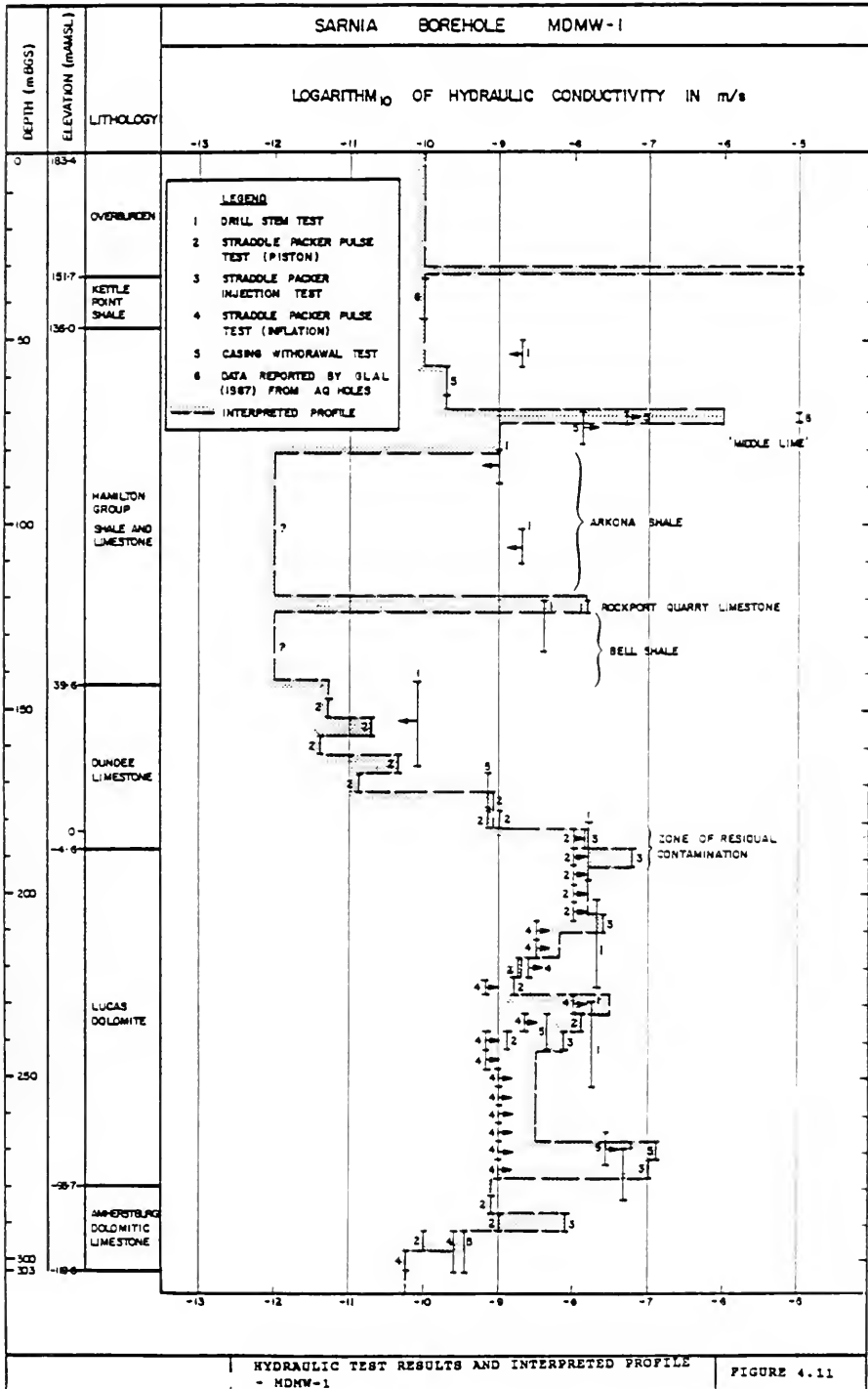
The upper sections of the Hamilton Group, likely in the Ipperwash shale and argillaceous limestone have hydraulic conductivity of about 1×10^{-10} m/s. A high hydraulic conductivity zone of 1×10^{-6} m/s or greater was measured at a depth of 70-74 m in a limestone bed likely within the Widder Formation. This horizon was also reported as having high hydraulic conductivity by GLAL/Esso (1987) at 1×10^{-5} m/s and flowed industrial waste during drilling in 1967 with an interpreted hydraulic conductivity of 7×10^{-5} to 7×10^{-5} m/s (see Section 2.2.4). The high hydraulic conductivity is also consistent with the observed gas production from this interval.

At 84 m the Hungry Hollow limestone is interpreted to have hydraulic conductivity less than 1×10^{-9} m/s and likely as low as 1×10^{-10} m/s.

Below 85 m depth, the Arkona shale is intersected and based on hydraulic conductivity measurements in similar shale sequences in southern Ontario are interpreted to have low hydraulic conductivity in the range 1×10^{-12} m/s.

The hydraulic conductivity of the Rockport Quarry limestone at 122-124 m depth was measured at about 2×10^{-3} m/s and this relatively high hydraulic conductivity is consistent with observed gas production from the formation.

Below the Rockport Quarry Formation the Bell Shale is intersected and this clay shale is similar to the Arkona shale and has interpreted hydraulic conductivity of about 1×10^{-12} m/s.

Hydraulic testing of the Dundee Formation limestone indicates hydraulic conductivity of 4×10^{-12} to 1×10^{-9} m/s generally increasing with depth toward the disposal horizon. The low hydraulic conductivities measured in the upper sections of the Dundee formation are attributed to the presence of crude oil in the pore space of the rock.

The interpreted hydraulic conductivity of the Lucas Formation ranges from 2×10^{-9} to 2×10^{-7} m/s with average hydraulic conductivities of 2×10^{-3}

m/s over the zone of residual contamination from about 187 to 203 m. One high hydraulic conductivity zone (i.e., 7×10^{-8} m/s) at 188.1 - 193.3 m depth contains the highest concentrations of industrial waste. In the core, this zone is characterized by dolomite with lenticular pores up to 15 mm diameter and bands of anhydrite.

High hydraulic conductivity zones within the Lucas Formation are also evident in the borehole at depths of 206-211 m, 228-240 m, and 268-278 m. The highest hydraulic conductivity measured in the Lucas Formation was at a depth of 268-273 m with a value of 2×10^{-7} m/s. In the core, this interval is characterized by zones of enhanced porosity with open vugs. This zone also corresponds to the geophysical features M and U discussed in Section 4.2.1.

The hydraulic conductivity of the Amherstburg Formation varies from 5×10^{-11} to 8×10^{-9} m/s generally decreasing with depth.

4.2.3   Hydraulic Head and Groundwater Flow

The results of all pressure profiles are listed in Appendix J. Appendix J lists the measurement port depth, the depth of the interval measured, the inside casing pressure in psia, the stable outside casing (formation) pressure in psia, the difference in pressure between these two readings and a calculated equivalent fresh water hydraulic head in m AMSL. Because the inside casing pressure measurements were always made with the water level to the top of the Westbay casing the difference in pressure between the inside and outside (formation) pressure readings were used to determine the equivalent fresh water hydraulic head of the formation. The relationship between change in pressure and equivalent fresh water head was:

$$h_f = Z_c + \frac{p_o - p_i}{\rho_f \, g}$$

where: h_f = equivalent fresh water hydraulic head (L);
          Z_c = elevation of top of Westbay casing, equal to
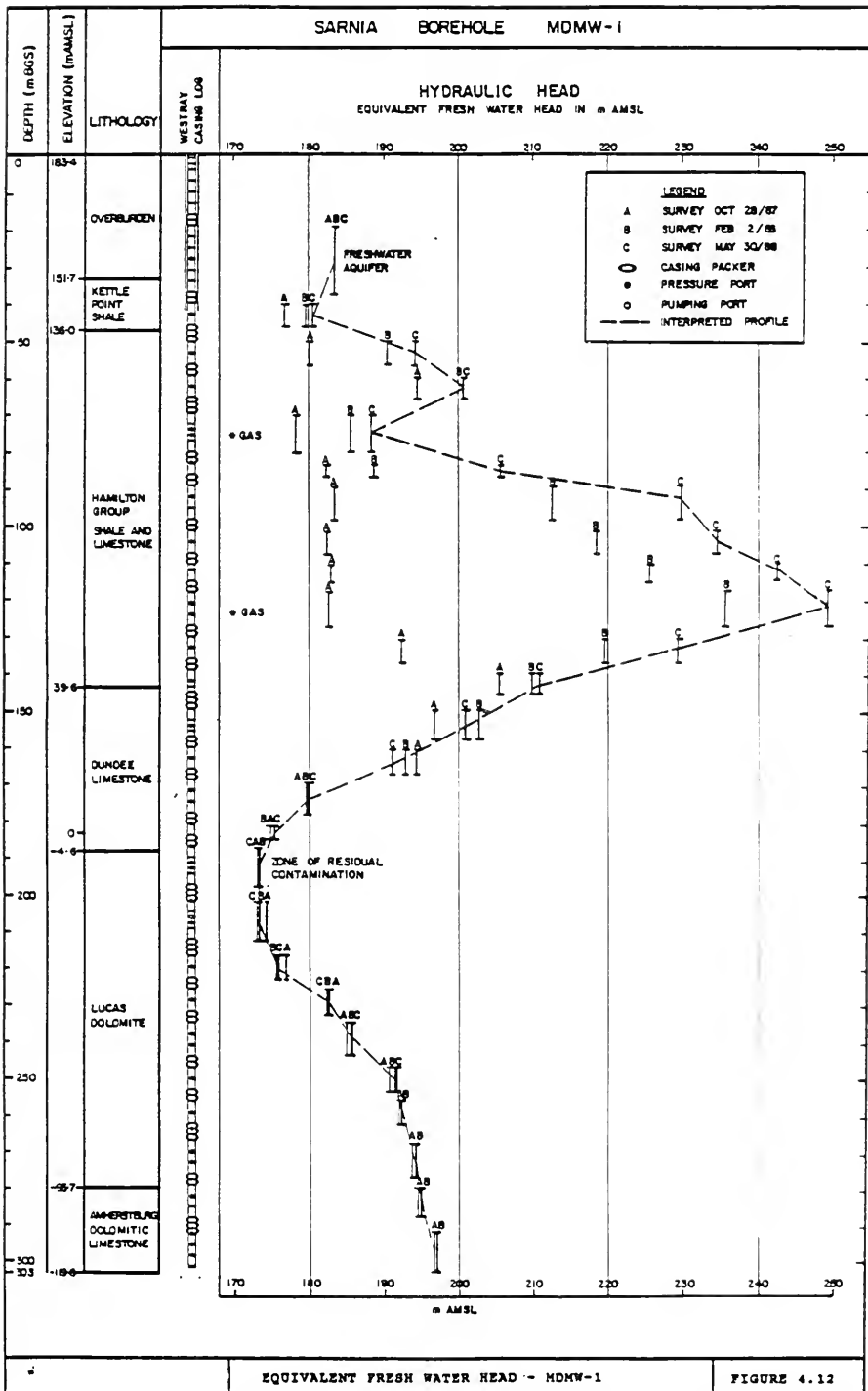   184.2 m AMSL;

p_o = outside casing pressure $(M/L \cdot T^2)$;

p_i = inside casing pressure $(M/L \cdot T^2)$;

ρ_f = fresh water density (M/L^3);

g = gravitational acceleration (L/T^2).

Expressing the measured formation pressures as equivalent fresh water heads is a convenient and consistent approach for comparing the heads in hydrogeologic systems consisting of variable density formation fluids (Lusczynski, 1961; Bond, 1972; Jorgensen et al., 1982). Equivalent fresh water heads define hydraulic gradients only along a horizontal plane (Lusczynski, 1961).

Figure 4.12 summarizes the geologic log, the Westbay casing installation log and the results of three pressure surveys performed on October 28, 1987, February 2, and May 30, 1988. The pressure surveys cover the seven month monitoring period from October 25, 1987 to May 30, 1988.

The pressure surveys expressed as equivalent fresh water heads show high heads in the Hamilton Group, low heads in the disposal zone of the Lucas Formation and increasing heads with depth through the Lucas Formation to the Amherstburg Formation. The interpreted head profile is the current best estimate of the equivalent fresh water heads in the borehole. More detailed discussion of the head distribution is provided below.

Figure 4.12 shows that the hydraulic heads within the Kettle Point Formation and Hamilton Group of Formations were very slow to reach equilibrium values and increases in recent surveys show that the pressures in these formation have yet to reach equilibrium values. The slow pressure increase in these formations is thought to reflect the presence of natural gas and the low hydraulic conductivity of the formations. In contrast the relatively high hydraulic conductivity tests intervals in the Detroit River Group of Formations rapidly reached equilibrium head conditions. The interlying Dundee Formation showed responses influenced by the responses in both the Hamilton and the Detroit River Groups.

SARNIA   BOREHOLE   MDMW-1

HYDRAULIC HEAD
EQUIVALENT FRESH WATER HEAD IN m AMSL

EQUIVALENT FRESH WATER HEAD - MDMW-1   FIGURE 4.12

The hydraulic head profile within the upper sections of the Dundee Formation and the Hamilton Group from about 85 to 143 m is apparently controlled by the gas production zone at 123 m from the Rockport Quarry Formation. In the May 30, 1988 survey the measured pressure was equal to a head of 67 m about ground surface. Above 85 m depth heads are influenced by a second high pressure zone at 64 m equal to a head of 18 m above ground surface. This zone is also a porous limestone bed. The gas production zone identified at 74 m during drilling and hydraulic testing does not show significantly high heads.

To estimate vertical flow potentials within borehole MDMW-1, it is necessary to correct the calculated equivalent fresh water heads for density differences between different formation fluids. The environmental water heads define the vertical gradients in flow systems with water of variable density and are determined by (Lusczynski, 1961):

$$h_e = h_f - \left(\frac{\rho_f - \rho_a}{\rho_f} \right)(Z_i - Z_r)$$

where: h_e = environmental water head (L);

Z_i = elevation of measurement point where equivalent fresh water head was determined (L);

Z_r = elevation of reference point from which the average density of water to i is determined and above which water is fresh;

ρ_a = average density of water between Z_1 and Z_r as defined by:

$$\rho_a = \frac{1}{Z_r - Z_1} \int_{Z_1}^{Z_r} \rho \, dz$$

Calculation of environmental water heads requires a fluid density profile within the formations and a reference elevation Z_r. The reference elevation Z_r was selected as the Fresh Water Aquifer at 151 m AMSL. The fluid density data determined from groundwater sampling are shown in Table 4.3.

Table 4.3: Summary of Interval Fluid Densities(*)
Borehole MOMW-1

Depth (m)	First Round Sampling	Second Round Sampling	Third Round Sampling	Fourth Round Sampling
61.5	-	1.02	1.02	1.02
75.0	1.04	1.04	1.03	1.03
123.0	1.04	1.04	1.03	1.02
180.0	1.04	1.03	-	-
192.5	-	1.04	1.03	1.03
207.0	1.11	1.05	1.04	1.04
228.0	-	-	1.13	1.12
240.0	1.13	-	-	1.13
271.5	1.13	-	-	-
290.0	1.13	-	-	-

(*) at 20 degrees Celsius in g/mL

The fluid densities range from 1.02 to 1.13 g/mL and the interpreted density profile is shown in Figure 4.13. Figure 4.13 also shows the equivalent fresh water head from the latest survey shown in Figure 4.12 and the environmental water head with respect to the Fresh Water Aquifer calculated using the density data. Table 4.4 gives the head data on which Figure 4.13 is based.

Table 4.4 and Figure 4.13 show that with correction for fluid density, the head within the zone of residual contamination at borehole MDMW-1 (i.e., port at 192 m depth) is 14.8 m below the head within the Fresh Water Aquifer. The environmental water head within the zone of residual contamination is 168.39 m AMSL which is also about 8 m below the level of the St. Clair River in the Sarnia area at 176.4 m AMSL.

Figure 4.13 also shows that with correction for fluid density the vertical gradients below the zone of residual contamination are reduced and may be reversed below 250 m. However the zone of residual contamination remains the lowest head feature in the borehole and has some natural hydraulic head confinement below (i.e., 13.7 m higher head to 250 m depth) and substantial hydraulic head confinement above (i.e., 78.5 m higher head up to depth 123 m). The hydraulic conductivity profile of Figure 4.11 also strongly suggests substantial natural confinement of the disposal horizon above by the Bell and Arkona shale sequences (hydraulic conductivity of about 1×10^{-12} m/s) and to a lesser extent below by Amherstburg dolomitic limestone (hydraulic conductivity of about 1×10^{-10} to 1×10^{-9} m/s). This natural hydraulic head and hydraulic conductivity confinement is offset by the existence of poorly completed and/or abandoned deep wells in the Sarnia area that hydraulically connect the Fresh Water Aquifer, the zone of residual contamination and intervening formations (URM, 1984).

The available head data shows that there is currently no fluid flow upwards or downwards from the zone of residual contamination and that horizontal flow within this zone is the significant flow direction of concern. There is however no reliable data to adequately assess the direction and magnitude of this

SARNIA BOREHOLE MDMW-1

HYDRAULIC HEAD m AMSL

EQUIVALENT FRESH WATER AND ENVIRONMENTAL
WATER HEADS - MDMW-1

FIGURE 4.13

Table 4.4   Summary of Equivalent Fresh Water Head and
            Environmental Water Head, Borehole MDMW-1

Port Depth (m)	Equivalent Fresh Water Head (mAMSL)	Environmental Water Head (mAMSL)
27.0	183.23	183.23
42.0	180.34	180.16
52.5	194.13	193.74
61.5	200.25	199.68
75.0	188.15	187.31
82.5	205.46	204.42
91.5	229.87	228.60
103.5	234.37	232.74
111.0	242.53	240.68
123.0	249.07	246.86
132.0	229.02	226.54
141.0	210.87	208.12
153.0	200.95	197.85
162.0	190.89	187.51
174.0	179.71	175.97
180.0	175.49	171.57
186.0	173.09	168.99
192.0	172.67	168.39
201.0	173.09	168.50
207.0	173.45	168.56
219.0	175.91	170.18
228.0	182.03	175.45
240.0	185.34	177.32
249.0	191.32	182.13
258.0	* 192.44	* 182.08
262.5	* 192.72	* 181.78
271.5	* 194.06	* 181.95
280.5	* 194.97	* 181.69
291.0	* 195.40	* 180.76
297.0	* 196.87	* 181.45

Note: All values refer to the May 30, 1988
        survey unless otherwise noted.
        * - February 2, 1988 survey.

horizontal flow. The one fluid level measurement reported by GLAL/Esso (1987) for disposal well DW2 was a measurement over a 50 m interval and is considered not representative of the likely narrow disposal zone identified in borehole MDMW-1.

Vertical fluid flow through the Hamilton Group in the absence of open boreholes or extensive vertical fracturing is not significant. Horizontal flow within selected high hydraulic conductivity limestone layers such as the Rockport Quarry Formation at 123 m depth and an unnamed limestone layer at 74 m depth in the Widder Formation is of greater concern because of the reported occurrence of industrial waste in the 74 m horizon and suspected occurrence of similar waste in the 123 m horizon. Assessment of lateral flow within these units requires other borehole measurements and only one measurement by GLAL/Esso (1987) for the 74 m depth limestone layer in the Widder Formation is available. This level of 176.37 m AMSL was an open borehole (AQ11) measurement in a gas producing horizon and therefore may be underestimated due to release of the gas pressure to atmosphere. The permeable horizon at 74 m depth in MDMW-1 has an equivalent fresh water head of about 188.15 m AMSL suggesting flow within the horizon toward the bedrock valley. It is likely that this bedrock horizon is eroded and exposed in the bedrock valley and groundwater and natural gas discharges from this horizon into the bedrock valley and into the Fresh Water Aquifer.

4.2.4   Groundwater Chemistry

The chemistry of the formation waters intersected by borehole MDMW-1 are described based on sampling during drilling and sampling during four sampling rounds using the Westbay casing. The water chemistry, as for the Fresh Water Aquifer, is described under the following sections:

- Drill Water Tracers;
- Environmental Isotopes;
- Major Ions;
- Metals;
- Total Phenols;

- Volatile Organics;
- Base Neutral Extractables;
- Acid Extractables;
- Organochlorine Pesticides and PCBs.

4.2.4.1 Drill Water Tracers. The measured concentrations of Lissamine FF and Iodide tracers in the drill water and subsequent water samples collected during the first and second sampling events are given in Tables 4.5 and 4.6. Table 4.5 summarizes the concentrations of tracer measured in each tank of drill water used during drilling. Average concentration of tracer in the drilling fluid was 5.2 mg/L Iodide and 125 ug/L Lissamine FF. Table 4.6 shows the measured concentrations of tracers in water samples collected from the first and second sampling rounds. The Lissamine FF tracer results, particularly above 210 m, are suspect due to organic fluorescence interference and the Iodide results are also suspect due to sulphide interference. The Iodide analyses reported in Table 4.6 were corrected for sulphide interferences through the addition of a metal acetate, however the background concentrations of Iodide in the deeper intervals may also be as high 1-2 mg/L. The Iodide data suggest drill water tracer concentrations of 30 - 80% of the sampled waters. For the deeper intervals (i.e., below 230 m) the measured iodide concentrations of 1.7 and 1.6 mg/L may be background values and drill water concentrations may be substantially less than the 30% suggested. Tritium isotope contents described in the following section confirm the lower concentrations of drill water in the deeper intervals and these analyzes are the most reliable indicators of drill water contamination.

4.2.4.2 Environmental Isotopes. The ^{18}O, ^{2}H, and ^{3}H contents of fluid samples collected from seven intervals in borehole MDMW-1 prior to first round sampling are given in Table 4.7. Table 4.7 also shows the isotope contents of a sample of the drill water (Sarnia City water) and St. Clair River water previously reported by Sklash et al. (1986).

Table 4.5: Summary of Tracer Concentrations in Drill Water -
Borehole MDMW-1

Sample Number			Sample Number			Sample Number			Sample Number		
T-1	I	4.2	T-11	I	6.4	T-21	I		T-31	I	3.4
	Lissamine	170.0		Lissamine	130.0		Lissamine	112.0		Lissamine	90.0
T-2	I		T-12	I	4.7	T-22	I		T-32	I	3.8
	Lissamine	70.0		Lissamine	95.0		Lissamine	174.0		Lissamine	122.0
T-3	I	3.0	T-13	I	4.7	T-23	I	5.8	T-33	I	
	Lissamine	140.0		Lissamine	128.0		Lissamine	120.0		Lissamine	
T-4	I		T-14	I	5.7	T-24	I	5.9	T-34	I	
	Lissamine			Lissamine	115.0		Lissamine	174.0		Lissamine	178.0
T-5	I		T-15	I		T-25	I	0.7	T-35	I	4.6
	Lissamine	46.0		Lissamine			Lissamine	26.0		Lissamine	95.0
T-6	I	4.8	T-16	I	5.9	T-26	I	4.7	T-36	I	4.5
	Lissamine	130.0		Lissamine	100.0		Lissamine	94.0		Lissamine	160.0
T-7	I	7.0	T-17	I	6.0	T-27	I		T-37	I	
	Lissamine	96.0		Lissamine	175.0		Lissamine			Lissamine	116.0
T-8	I	8.2	T-18	I		T-28	I	6.0	T-38	I	
	Lissamine	136.0		Lissamine	134.0		Lissamine	260.0		Lissamine	130.0
T-9	I	12.0	T-19	I	6.2	T-29	I		T-11b	I	3.5
	Lissamine	162.0		Lissamine	175.0		Lissamine	190.0		Lissamine	50.0
T-10	I	3.9	T-20	I		T-30	I	4.7			
	Lissamine	70.0		Lissamine	100.0		Lissamine				

Note: Iodide concentrations in ppm
Lissamine concentrations in ppb
Average I concentration = 5.21 ppm
Average Lissamine concentration = 125.4 ppb

Table 4.6: Summary of Tracer Concentrations in Sampled Waters -
Borehole MDMW-1

Depth Interval (m)	FIRST ROUND Iodide (ppm)	FIRST ROUND Lissamine (ppb)	SECOND ROUND Iodide (ppm)	SECOND ROUND Lissamine (ppb)
61.5	-	-	2.2	12.0
75.0	1.6	12.0	3.6, 2.1	10.0
123.0	2.8	10.0	4.5	8.0
174.0	3.0	-	-	-
180.0	2.0	10.0	4.5	0.8
192.5	3.0	-	2.8	6.0
207.0	2.0	17.5	3.6	15.0
240.0	1.7	14.0	-	-
271.5	1.6	6.0	-	-
291.0	-	14.0	-	-

Table 4.7   Environmental Isotope Analyses - Borehole MDMW-1

Sample Depth m BGS	$\delta^{18}O$ ‰	δ^2H ‰	^3H TU
75	-7.26	-49.8	22 +/-8
		-50.7	22 +/-8
123	-6.94	-46.0	19 +/-8
174	-5.91	-47.4	26 +/-8
192	-6.84	-44.4	32 +/-8
		-43.0	
207	-6.54	-44.6	31 -/-8
240	-3.54	-29.3	<6 -/-8
271.5	-1.34	-24.7	8 +/-8
Drill Water (Sarnia City Water)	-7.17 to -7.35	-56.7	72 +/-8
Drill Water* (St. Clair River)	-7.25	-58.0	89 +/-8

* Data reported by Sklash et al. (1986)

The tritium contents of the samples vary from <6 to 32 TU with the deeper samples containing the lowest tritium concentrations and the zone of residual contamination at 192 m and possibly 207 m having the highest tritium concentrations. Assuming the tritium content of the drill water was 80 TU, and that industrial waste injected in the Sarnia area contained no tritium, the maximum drill water contamination of the samples ranges from 0 to 40%. If the industrial waste contained tritium (and it is likely that it did) the actual drill water contamination levels in intervals with waste would be less.

The tritium contents are generally consistent with the borehole and formation hydraulics described in Sections 4.2.2 and 4.2.3 in that those intervals (i.e., at 75, 123, 240 and 271.5 m) with hydraulic head greater than the drilling and open borehole fluid levels had less influx of drill fluid to the formation and generally have lower tritium contents. Similarly the intervals at 192 and 207 m in the disposal zone had low formation hydraulic heads and therefore accepted greater volumes of drill fluid and have higher tritium contents.

Because the borehole was open for a period of about four weeks, cross formational flow principally from the high head deeper sections of the borehole containing brine to the low head disposal zones at 190-220 m was a significant but difficult to quantify mode of formation water contamination. Because the drill water and deep brine have characteristic tritium and chloride contents, a plot of tritium versus chloride provides some insight to the extent to which the first round and to a lesser extent the later round samples may contain drill water and/or the deep brine. Figure 4.14 shows the tritium chloride plot and the zone of mixing between the deep brine and the drill water. Figure 4.14 shows that the early samples (i.e., first round) from depth 207 m fall on the mixing line between drill water and deep brine and may contain only a small percentage of natural formation water. Samples from 192, 174, 75 and 123 m plot progressively farther from the mixing line and therefore contain progressively higher contents of natural formation water. This observation is consistent with

TRITIUM (^{3}H) - CHLORIDE PLOT,
BOREHOLE MDMW-1

FIGURE 4.14
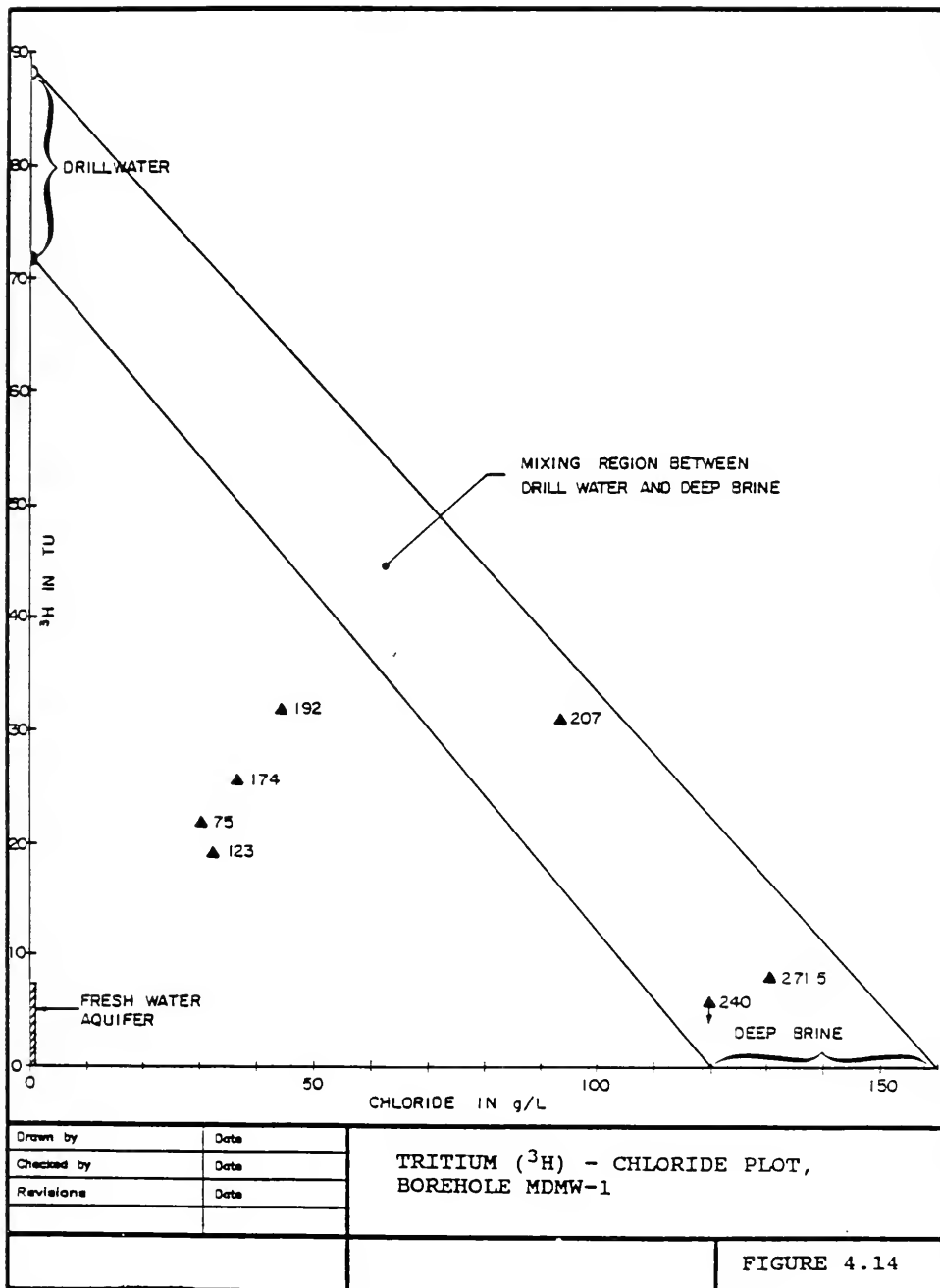
the known well and formation hydraulics. In particular, the zone at 207 m has similar low head to the interval at 192 m and therefore considerable flow of brine from depth was likely accepted by the zone at 207 m before reaching the interval at 192 m depth.

Figure 4.15 is the δ^2H - $\delta^{18}O$ plot with the meteoric water line of the Fresh Water Aquifer determined in Section 3.2.5.2. Figure 4.15 shows that the deep brine waters (>220 m depth) are enriched in ^{18}O and plot below the meteoric water line suggesting isotopic exchange with carbonate minerals in the rock formations. Similar ^2H and ^{18}O contents have been measured for middle Devonian brines from the Michigan Basin by Wilson and Long (1986). Figure 4.15 also shows that most of the samples collected from 75-207 m plot above the meteoric water line and likely reflect isotopic exchange with H_2S, a significant component of the waters at these depths.

4.2.4.3   Major Ions. The major ion chemistry of the waters sampled from the deep borehole are given in Appendix K1. Appendix K1 summarizes the major ion chemistry of samples collected during drilling and later after casing installation. These analyses show there is spatial and temporal variability in the chemistry of sampled waters. There is an increase in total dissolved solids with depth and later samples collected from the third and fourth sampling rounds are more representative of formation waters than waters from earlier sampling rounds due to contamination of interval water by drilling fluids and cross formational flow. In general all sampled waters are Na-Cl brines or saline waters with Ca-SO$_4$ as the second most dominant ion group.

Figure 4.16 summarizes the chloride data for all sampling rounds for all intervals and is representative of trends in major ion chemistry. Figure 4.16 shows that the chloride contents range from 20,000 to 160,000 mg/L increasing with depth, particularly below 210-220 m depth and that the most reliable measures of formation water are likely from the third and fourth sampling rounds.
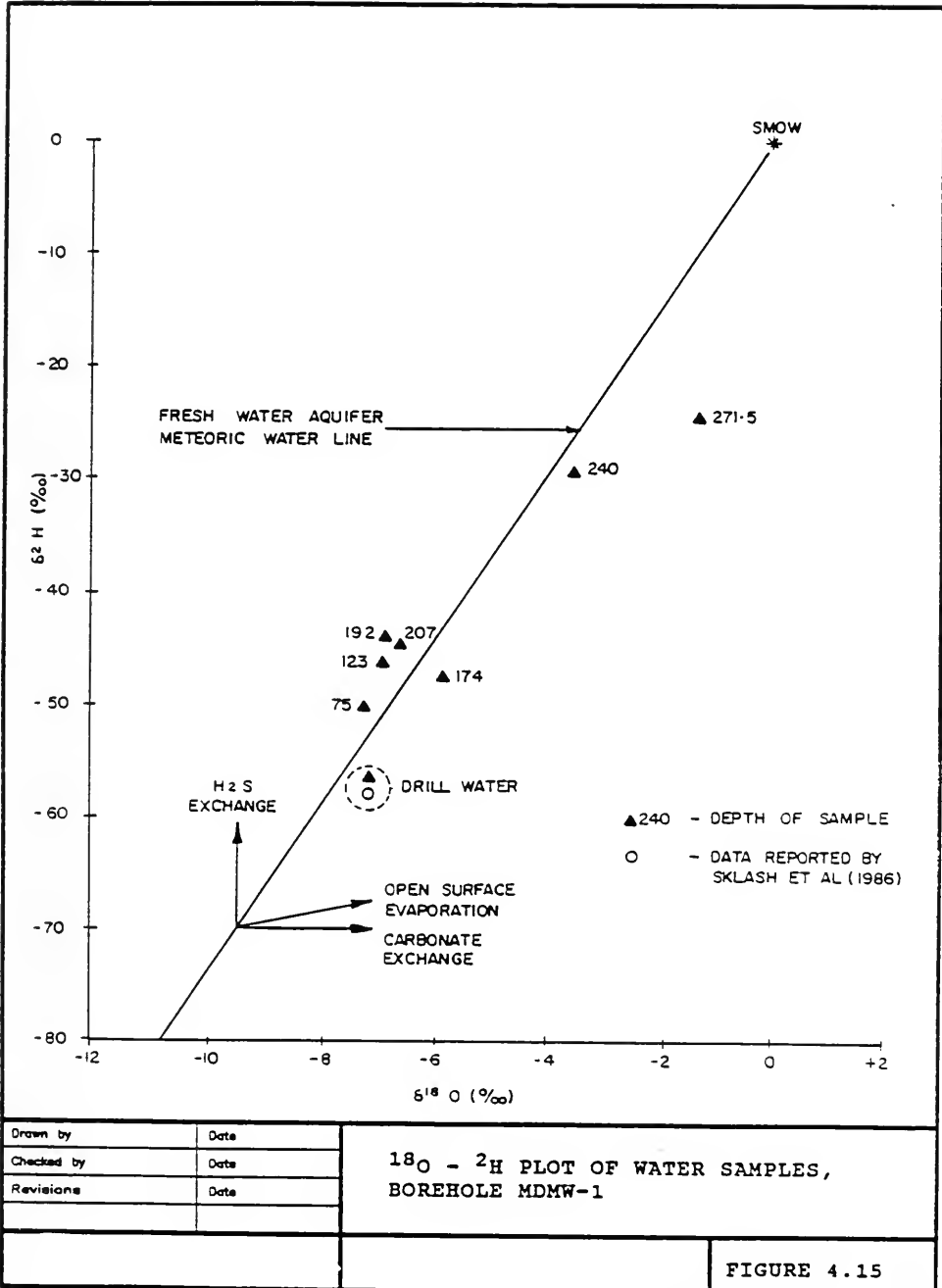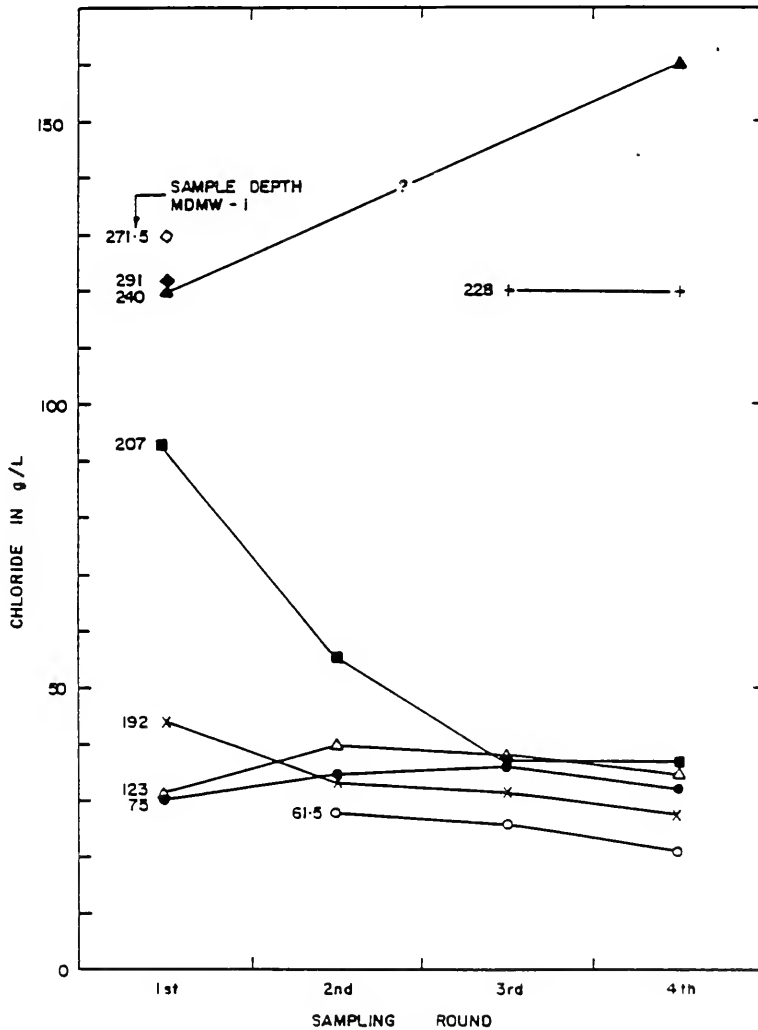
^{18}O – ^{2}H PLOT OF WATER SAMPLES, BOREHOLE MDMW-1

FIGURE 4.15

VARIATION OF CHLORIDE WITH SAMPLING
ROUNDS, BOREHOLE MDMW-1

FIGURE 4.16

The waters sampled from depths of 61.5, 75 and 123 m show chloride concentrations that are relatively stable over the four sampling rounds and are likely representative of formation water chemistries due to the high hydraulic heads in these formations and the fact they have likely produced fluid to the borehole throughout the period of open borehole conditions. The intervals at 192 m and particularly 207 m in the disposal horizon show reductions in chloride concentration through the first few sampling rounds, that are indicative of removal and natural flushing of the high chloride brines introduced to these intervals from deeper sections of the borehole during open borehole conditions. The drop in chloride is greatest in the interval at 207 m depth consistent with the interpretation of the tritium-chloride data discussed in Section 4.2.4.2 and Figure 4.14.

Below 210-220 m the formation waters are Na-Cl brines with chloride concentrations from 120,000 to 160,000 mg/L. The limited data from the deep intervals show that the chloride concentrations are stable or increase through the sampling rounds. A very high chloride concentration of 246,000 mg/L was measured on a sample collected during drilling at 247.5 - 260.3 m depth. This sample was an isolated sample in that it was not possible to collect similar samples to confirm the reliability of the analytical result. Because the result is substantially higher than subsequent analyses performed on water samples collected from the Westbay casing at similar depths it is possible that the result may not be representative. The representativeness of the high chloride value could be evaluated by ion balance considerations, however, sodium and calcium contents for the sample were not reported by the laboratory and therefore the representativeness of the chloride analysis is suspect. Because of the high formation heads and low tritium contents the samples collected from the Westbay casing from below 220 m are considered representative of formation waters.

The rapid reduction in chloride concentration from 93,000 to 38,000 mg/L between the first and third sampling rounds of the 207 m depth interval is much greater than would be expected if withdrawal of fluid for sampling was the only mechanism for purging of the interval. The reduction in chloride concentration suggests that natural flushing of the interval by

groundwater flow is significant at this depth and therefore that a relatively active flow system currently exists within sections of the disposal horizon. The relatively low chloride concentrations of 35,000 - 40,000 mg/L in the zones at 185.7 to 211.6 m depth compared to the much higher chloride concentrations below 220 m depth (>120,000 mg/L) indicates a relatively active flow in the 185.7 to 211.6 m horizon as compared to the deeper sections of the Detroit River Group. This flow may be from previously disposal operations or as suggested above, an active flow system within sections of disposal formation today.

The major ion chemistry reported in Appendix K1 also indicates considerably elevated alkalinity in the disposal horizon at 192 m depth indicating residual industrial waste. Alkalinities of 720 and 830 mg/L $CaCO_3$ were reported from the third and fourth sampling rounds at 192 m depth as compared with alkalinities of 130 to 440 mg/L $CaCO_3$ for other intervals in the borehole.

4.2.4.4   Metals.   The metals analyses are also given in Appendix K1. Appendix K1 shows that the metals concentrations are generally low within the sampled waters due principally to the very high sulphur and sulphide concentrations and the generally low solubility of metal sulphides. Sulphur was measured during the third and fourth sampling rounds and the concentrations ranged from 400 to 12,000 mg/L generally increasing with depth from 61.5 to 228 m, and diminishing to 1400 mg/L at 240 m depth.

4.2.4.5   Phenols.   The phenol concentrations of water sampled from the deep borehole are summarized in Table 4.8 based on analyses performed by Ontario Ministry of the Environment (London), Zenon Environmental Inc. (Burlington) and Barringer-Magenta Ltd. (Rexdale). The analyses by MOE and Zenon Environmental Inc. are based on the colourimetric 4AAP method and the analyses by Barringer-Magenta Ltd. are by GC/MS (Appendix K4). The GC/MS analyses listed in Table 4.8 are also graphically displayed in Figure 4.17. The phenol concentration data in Figure 4.17 are plotted as the common logarithm of phenol concentration in ug/L.

Table 4.8 and Figure 4.17 show that the highest phenol concentrations of 30,000 - 40,000 ug/L were measured in the interval at 192 m depth in the disposal zone and that the underlying interval at 207 m depth contains much lower levels of phenol at 50 - 206 ug/L. The deeper intervals at 228, 240, 271.5 and 291 m depth contain very low levels of phenol typically less than 10 ug/L. These phenol data identify the preferred disposal horizon or the zone of residual contamination as being centred at 192 m depth (i.e., interval 185.7 - 196.6 m depth).

The phenol concentrations in those intervals overlying the zone of residual contamination (i.e., 180, 123, 75 and 61.5 m depth) ranged from 1000 - 6000 ug/L. The interpretation of these phenol data is complicated by the fact that phenols near these levels are associated with natural petroleum products and the crude oil produced from the Dundee Formation at 170 - 180 m depth migrated upward past these intervals to surface. It is possible that some crude

Table 4.8:   Summary of phenol, pH and conductivity results - Borehole MDMW-1

PARAMETER	2nd Round 61.5m	3rd Round 61.5m	4th Round 61.5m	1st Round 75m	2nd Round 75m	2nd Round Duplicate 75m	3rd Round 75m	4th Round 75m
pH	-	-	* 7.51	-	7.07	7.07	-	* 7.54
Conductivity (umhos)	-	28500	-	* 44400	29900	29900	33000	-
Phenols (ug/L) **	2900	2225	2750	3520	3700	3700	2775	3500
Phenols (ug/L) ***	2290	1010	2480	2290	1240	958	1280	6120

PARAMETER	1st Round 123m	2nd Round 123m	3rd Round 123m	3rd Round Duplicate 123m	4th Round 123m	4th Round Duplicate 123m	1st Round 180m	2nd Round 180m
pH	6.82	6.61	-	-	* 7.9	* 7.89	6.52	-
Conductivity (umhos)	* 47100	* 33000	39500	-	-	-	* 48100	-
Phenols (ug/L) **	4950 *	5400	4500	4400	* 2900	* 2800	4600	5000
Phenols (ug/L) ***	1310	2570	1510	-	4420	4560	1640	3080

PARAMETER	1st Round 192m	2nd Round 192m	3rd Round 192m	4th Round 192m	1st Round 207m	2nd Round 207m	3rd Round 207m	4th Round 207m
pH	6.82	6.95	-	* 8.74	6.02	6.29	-	* 7.75
Conductivity (umhos)	* 53400	33000	37000	-	* 104000	43500	51000	-
Phenols (ug/L) **	455	67000	52000	* 22000	302	440	4100	* 730
Phenols (ug/L) ***	31000	30900	37400	39700	132	<57	90.7	206

*   Analysis by Zenon Environmental Inc.

**   Analysis by Ministry of Environment Laboratories (London) unless otherwise indicated

*** Analysis by Barringer Magenta Ltd.

-    Analysis not performed

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Table 4.8:   Summary of phenol, pH and conductivity results -
Borehole MDMW-1 (cont'd)

PARAMETER	3rd Round 228m	4th Round 228m	1st Round 240m	4th Round 240m	1st Round 271.5m	1st Round 291m
pH	-	* 6.72	6.09	* 7.13	6	6.1
Conductivity (umhos)	>60000	-	* 117000	-	* 117000	* 116000
Phenols (ug/L) **	260	* 67	-	* 27	-	-
Phenols (ug/L) ***	5.5	3.9	<3.7	2.3	<3.7	5.2

PARAMETER	1st Equipment Rinse	2nd Equipment Rinse	3rd Equipment Rinse	4th Equipment Rinse
pH	-	-	-	* 6.25
Conductivity (umhos)	* 2.7	-	-	-
Phenols (ug/L) **	<1.0	<1.0	<1.0	<1.0
Phenols (ug/L) ***	<0.5	0.6	<0.5	<0.5

*   Analysis by Zenon Environmental Inc.
**   Analysis by Ministry of Environment Laboratories (London) unless otherwise indicated
*** Analysis by Barringer Magenta Ltd.
-    Analysis not performed
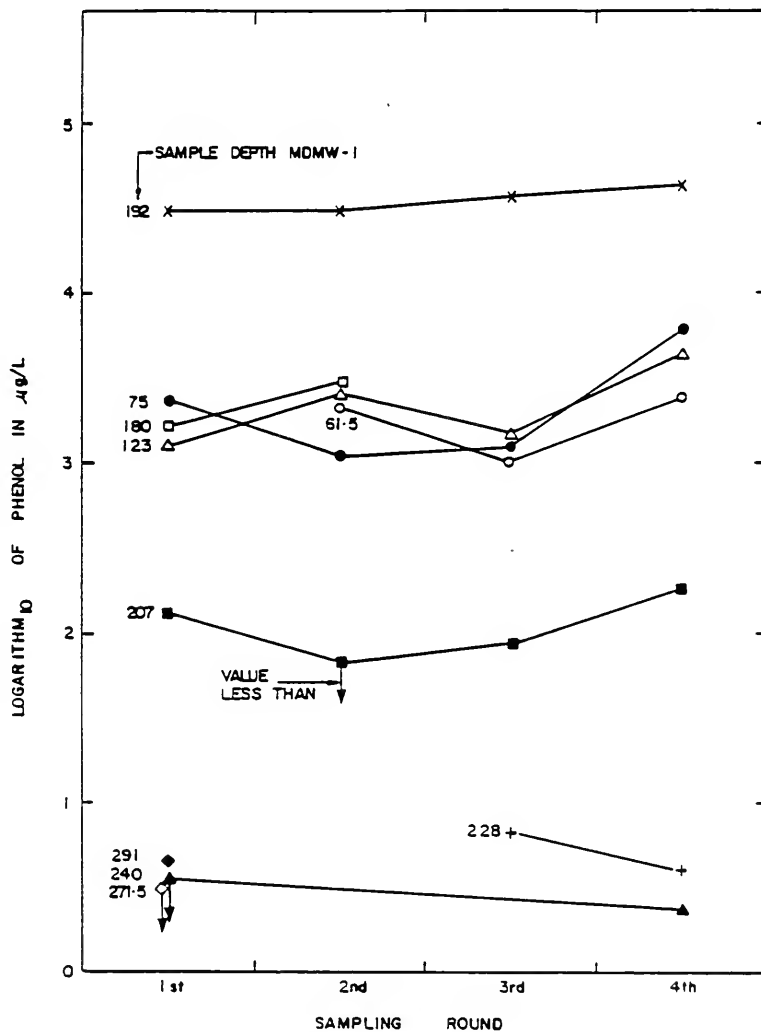
VARIATION OF PHENOL WITH SAMPLING
ROUNDS, BOREHOLE MDMW-1

FIGURE 4.17

oil may have been affixed to the borehole wall in these overlying intervals and the measured phenol levels reflect the contamination of these intervals by the crude oil from the Dundee Formation. Slightly higher levels of phenol measured during the fourth sampling round for intervals at 75 m (6120 ug/L) and 123 m (4560 ug/L) in conjunction with 1967 and 1969 drilling experience (Section 2.3.3) and the observations made during drilling MDMW-1 suggest that the phenols concentrations at 75 and 123 m depth are a measure of both industrial waste and crude oil contamination.

4.2.4.6 <u>Volatile Organics</u>. Appendix K2 summarizes the volatile organic analyses of the deep borehole performed in this study. Appendix K2 shows that the principal volatile organic compounds detected in the borehole were benzene, toluene, ethylbenzene, xylenes, and methylbenzenes. The highest concentrations of these compounds was measured at 192 m depth during the third sampling round. These compounds and concentrations from the third sampling round were benzene 1580 ug/L, toluene 5880 ug/L, ethylbenzene 1630 ug/L, m-xylene and p-xylene 4470 ug/L, o-xylene 2190 ug/L, methylbenzenes 256 to 742 ug/L.

Volatile organic compounds were also detected at similar although slightly lower concentrations at depths of 61.5, 75, 123 and 180 m depth. The interpretation of the analytical results, as with the phenol results, is not straight forward because the detected compounds are also associated with natural petroleum products . Also the volatile organic analyses show considerable variability within sampling rounds due to sampling methodology.

Lower concentrations of volatile organic compounds were measured in intervals at 207, 240, 271.5 and 291 m depth. These lower levels of volatile organics are likely associated with crude oil seams detected in the core at these depths.

Significantly the industrial waste detected at the 192 m level does not contain chlorinated volatile organics such as perchloroethylene and carbon tetrachloride and therefore is chemically dissimilar to the waste pools ("blobs") detected on the bottom of the St. Clair River in 1985.

4.2.4.7   Base Neutral Extractables. The analyses of water samples from borehole MDMW-1 for base neutral extractable compounds are given in Appendix K3. Naphthalene, and methlynaphthalenes were the significant base neutral extractable compounds detected in the deep borehole.

The highest concentrations of naphthalene and methylnaphthalenes were detected within the disposal zone at a depth of 192 m. Samples collected from this zone of residual contamination during drilling (sample MD-1) and later from four sampling rounds showed naphthalene at less than 50 to 829 ug/L levels and methylnaphthalenes at less than 50 to 199 ug/L.   The naphthalene and methylnaphthalene levels are diagnostic of the disposal zone as much lower levels were detected in the overlying and underlying intervals. Samples from 61.5, 75, 123 and 180 m showed naphthalene at 4.9 to 16.7 ug/L and methylnaphthalenes at 1.6 to 11.5 ug/L. Samples from 207, 228, 240, 271.5 and 291 m showed naphthalene at less than 0.5 to 5.9 ug/L and methylnaphthalenes at less than 0.5 to 4.3 ug/L. No significant levels of naphthalene and methylnaphthalene were detected below 207 m depth. Low levels of naphthalene (14.5 ug/L) and methylnaphthalene (6.9 ug/L) were measured in the second round equipment rinse (sample MDMW-1-R2) suggesting that levels below 5-7 ug/L are insignificant. Low levels of two polycylic aromatic hydrocarbons (fluorene at 6.8 ug/L and phenanthrene at 13.3 ug/L) were detected in the drilling sample of the zone of residual contamination.

4.2.4.8   Acid Extractables.   The analysis of MDMW-1 samples for extractable compounds are listed in Appendix K4. Acid extractable phenol concentrations are also listed in Table 4.8. The data in Appendix K4 indicate that significantly elevated levels of phenol (30,900 to 39,700 ug/L) and 2-4 dimethylphenol (less than 100 to 1020 ug/L) characterize the zone of residual contamination at 192 m depth. Lower levels of phenol and 2-4 dimethylphenol were detected above and below this zone of residual contamination. The phenols present in the intervals overlying the disposal formation in part reflect the acid extractable compounds associated with natural petroleum products.

Because phenols were the major component of the injected wastes, a detailed examination of the mass spectra of the acid extractable compounds from the third and fourth sampling rounds was performed to determine if these data could provide information on the source of the phenols in the upper 61.5, 75 and 123 m depth intervals. Review of the mass spectra shows that the greatest number of different phenol compounds occurs within the zone of residual contamination (192 m) followed by the 123 m interval and the 75 and 61.5 m intervals. Only 2-4-dimethylphenol and 2-methylphenol were detected in zones below the 192 m interval. Although similar phenol compounds were detected in the 61.5, 75 and 123 m depth zones as in the disposal zone, it was not possible, based on the available phenol mass spectra, to positively identify these phenols as being from the same source.

The acid extractable mass spectra also showed that significant levels of organosulphur compounds were present in the intervals at 61.5, 75 and 123 m. These compounds are interpreted to be associated with biogenic gas production at these depths.

4.2.4.9 Organochlorine Pesticides and PCBs. Appendix K5 contains the analytical results for organochlorine pesticides and PCBs for the deep borehole samples. No significant levels of organochlorine pesticides and PCBs were detected in the collected water samples. Very low levels of hexachlorobenzene were detected in sample MDMLS-2 at 0.0060 ug/L, of heptachlor in one of the 61.5 m samples at 0.0016 ug/L and of Aldrin in the disposal horizon sample collection during drilling at 0.0031 ug/L. These levels are insignificant as levels of hexachlorobenzene of up to 0.0050 ug/L were detected in trip and reagent blanks, and Aldrin was detected in sampling equipment rinses at levels of 0.0030 ug/L.

5. COMPUTER MODELING OF THE FRESH WATER AQUIFER AND DEEP
    GEOLOGIC FORMATIONS

5.1   INTRODUCTION

The computer modeling performed as part of this study was undertaken
to fulfill the following objectives:

1. Develop a detailed representation of the groundwater flow system
    of the Fresh Water Aquifer to evaluate the major and minor factors
    controlling groundwater flow within the aquifer and to determine
    groundwater and contaminant discharge to the St. Clair River.

2. Evaluate the potential size of contaminant plumes in the Fresh
    Water Aquifer that could exist due to the vertical migration of
    waste from the disposal zone through an abandoned borehole.

Initially, the modeling exercise was to examine the flux of
contaminants from the Aquifer to the St. Clair River but because there was no
appreciable contamination found in the Aquifer, the objectives of the modeling
were changed to consider the potential impact of a contaminant plume discharging
into the Aquifer from an abandoned borehole.

The modeling objectives were achieved through the completion of the
following modeling tasks.

1. Development of a steady state numerical flow model of the Fresh
    Water Aquifer;

2. Simulation of the disposal formation and confining layers during
    a representative waste injection period;

3. Simulation of the generation and migration of potential contaminant plumes within the Fresh Water Aquifer;

All modeling simulations were conducted using INTERA's SWIFT II model. This model has the following characteristics/features:

- solves groundwater flow and transport equations for heat, trace contaminants, brine and decaying substances;
- can be used in one, two or three-dimensional mode in either radial or cartesian co-ordinates;
- uses a finite difference method;
- applicable to porous or fractured media;
- can simulate a variety of boundary conditions, e.g., constant or variable potential, flux, infinite aquifer boundary;
- can be used in either steady state or transient mode;
- wells are incorporated explicitly into the model and can be either rate or pressure limited.

The SWIFT model which was developed in 1976 has gained widespread acceptance by the groundwater community and is recognized as one of the most widely used and thoroughly tested models currently available. The model has been described in detail by Reeves et al. (1985) with earlier versions documented by Dillon et al. (1978) and INTERCOMP (1976).

5.2   MODEL DESCRIPTION AND RESULTS

5.2.1   Fresh Water Aquifer Flow Model

A flow model of the Fresh Water Aquifer was constructed based on the results summarized in Sections 3 and 4 of this report. Information on the geology depth, thickness, extent, hydraulic conductivity and hydraulic head of the Fresh Water Aquifer were used in developing the flow model.

The finite difference method employed by SWIFT II to solve the partial differential groundwater flow and transport equations, requires that a grid or mesh be employed to represent the area to be modeled. The constructed model of the Fresh Water Aquifer was two-dimensional (areal) and employed over 2000 grid blocks to represent the approximately 11 km by 16 km region shown in Figure 5.1. For simplicity a uniform hydraulic transmissivity of 1×10^{-5} m^2/s was used to represent the Fresh Water Aquifer. This is equivalent to the geometric mean of hydraulic conductivity determined from all hydraulic tests performed outside of the bedrock valley (5×10^{-6} m^2/s) and formation thickness of 2.0 m. The higher hydraulic conductivity measured in the bedrock valley particularly at the north end of Esso Petroleum Canada property was not explicitly incorporated in the model and therefore the model's fits are expected to be poorer in these areas.

The elevation of the Fresh Water Aquifer was assumed to follow the bedrock surface and was varied spatially to reflect the differences in the elevation of the bedrock surface shown in Figure 3.4.

Two types of boundary conditions were used in the model; edge and surface.

Edge boundary conditions were either no-flow or constant pressure. Constant pressure boundary conditions were used along the southern and eastern edges based on equilibrium hydraulic head data from monitoring wells 7-87 and 9-87, respectively. All other edges of the model were assumed no-flow. This includes the western edge of the model corresponding to the middle of the St. Clair River which implies that for the Fresh Water Aquifer no water flows under the River and all water discharges to the River. This approach was adopted because available hydrogeologic data (Section 2.2.2) for the Fresh Water Aquifer on the U.S. side indicate that groundwater flow is a mirror of that on the Canadian side and is to the St. Clair River.

Surface pressure boundary conditions were employed to represent the water levels of the St. Clair River and Lake Huron for those grid blocks located

PORT HURON

CORUNNA
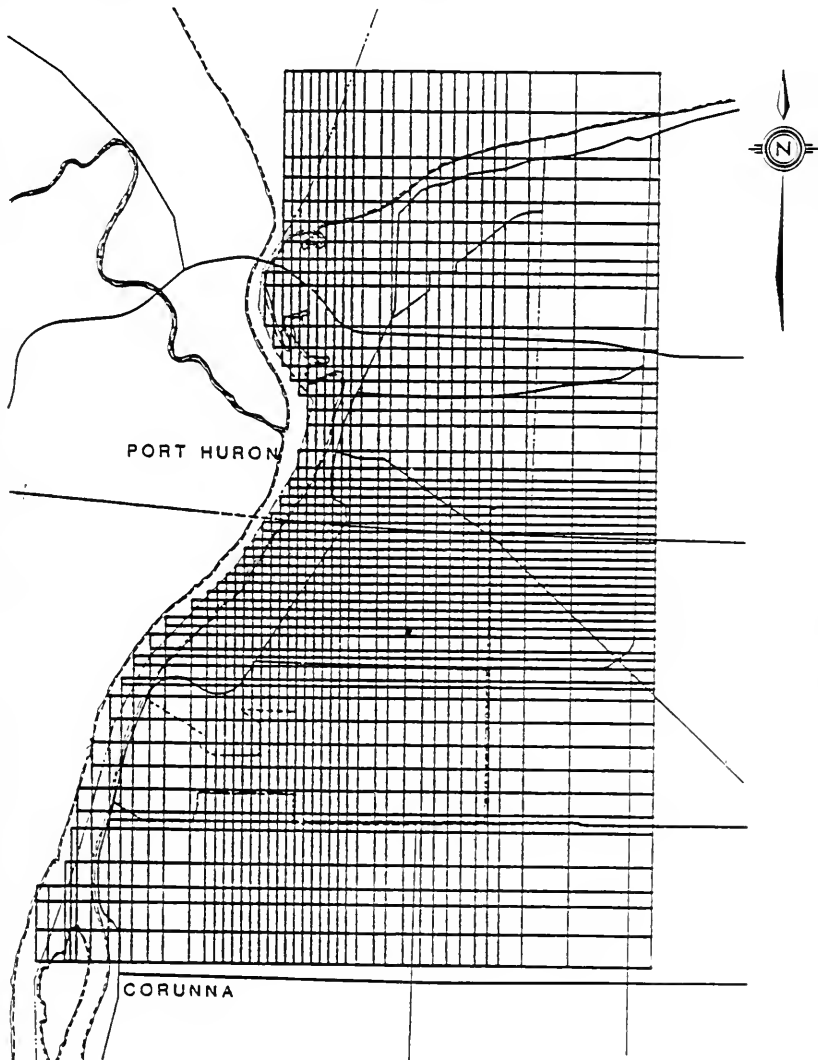
| Drawn by	Date	FINITE DIFFERENCE GRID USED TO
Checked by	Date	MODEL FRESH WATER AQUIFER
Revisions	Date	

SCALE
0 1 2 3 km

FIGURE 5.1

below these water bodies. To account for the surficial deposits (including alluvium and till) underlying these water bodies, the vertical transmissivity of the blocks under these water bodies was modified. As a result the vertical transmissivity (hydraulic conductivity x area/vertical distance) between the grid block centre and the constant pressure imposed on the top of the block corresponds to approximately 10 m of 2×10^{-10} m/s till. Although some thickness of till overlying the Fresh Water Aquifer below the St. Clair River are less than 10 m, these occurrences will not impact the results of the flow modeling.

The last type of boundary condition was a surface flux distributed evenly over the grid. This flux represents recharge to the Fresh Water Aquifer through the till minus or plus any loss or gain to or from the underlying bedrock. The downward flux was estimated at about 5×10^{-12} m/s based on average advective fluxes of about 0.1 mm/a used by Desaulniers (1986) to simulate ^{18}O and chloride profiles in the tills at Sarnia. The losses or gains of fluid to or from the underlying bedrock were assumed to be negligible because of the low hydraulic conductivity of unfractured Kettle Point shale and the uncertainty in head relationships between the Fresh Water Aquifer and the shale.

The results of the model simulations are shown in Figure 5.2. Figure 5.2 shows a comparison of the calculated steady state head values (contoured values) and the measured hydraulic head values from the monitoring well survey of January 19, 1988. Generally the fit between the model and field data is good with major trends in the potentiometric surface being reproduced by the model (see Figure 3.7 for comparison). Deviations between the model results and field data occur principally in areas of the bedrock valley where the Aquifer thickness, hydraulic conductivity and head relationship to the underlying formations is uncertain. The deviations between the model results and the field data are noticeable in some areas of the Esso Petroleum Canada property in the area of the bedrock valley and in the southwest section of the study area immediately south east of the bedrock valley. In both instances the field hydraulic head data are less than the model simulation indicating some component of downward flow from the Fresh Water Aquifer to the underlying formations is occurring. In these locations the model overpredicts the groundwater discharge rate to the St. Clair River by an uncertain amount.
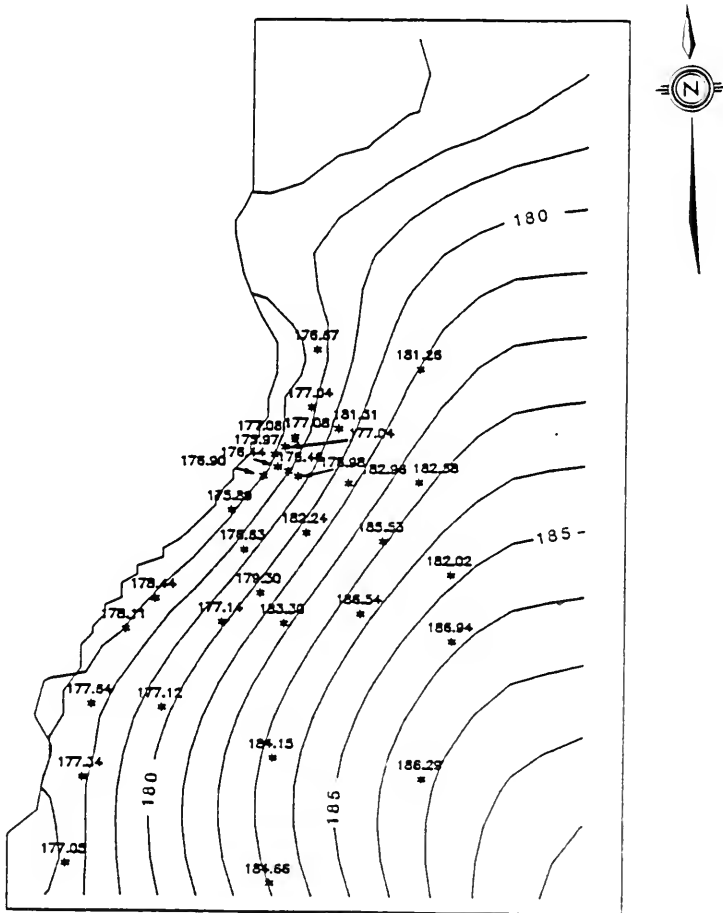
COMPARISON OF MODEL CALCULATED
(CONTOURS) AND MEASURED HYDRAULIC
HEADS FOR FRESH WATER AQUIFER

FIGURE 5.2

In the central section of the study area southeast of the bedrock valley, the model simulates both lower and higher head values then the measured values. These differences are thought to reflect the local heterogeneity of the hydraulic conductivity of the Fresh Water Aquifer as indicated in Section 3.2.3. Given the patchy nature of the aquifer, such underestimation and overestimation of hydraulic heads by a model based on homogeneous hydraulic properties is expected and is not considered significant.

Discharge of groundwater from the Canadian side of the Fresh Water Aquifer to the St. Clair River is calculated by the model as approximately 7500 m^3/a for the section of River between Lake Huron and Stag Island. Over this 13 km length the average discharge per unit width of aquifer is 0.57 m^3/a. This value is similar to the flux of 0.5 m^3/a from the Fresh Water Aquifer to the bedrock valley calculated in Section 3.2.4 using Darcy's Law.

5.2.2   Disposal Well Model

The second objective of the modeling study was to evaluate the size of potential contaminant plumes in the Fresh Water Aquifer due to the presence of an abandoned borehole hydraulically connecting the disposal formation to the Fresh Water Aquifer. These calculations were meant to be bounding calculations and to examine a range of conditions that could potentially exist. The following assumptions/values were made/chosen:

1. Abandoned borehole was unplugged and hydraulically connected the disposal zone and the Fresh Water Aquifer;

2. The borehole was likely located between 100 m to 1000 m from the injection well;

3. The thickness of the active zone of injection was between 1 m and 65 m with a most likely value of 10 m;

4.   Pressure and contaminant interference effects from other disposal wells are ignored.

Before an evaluation of the flux moving through an abandoned borehole could be made, the behaviour of the disposal zone and the Fresh Water Aquifer were analyzed. To perform these analyses, a cylindrical model of the horizons between the Detroit River Group and the Fresh Water Aquifer was constructed. This model was constructed using the geologic definition and hydraulic conductivity distribution of borehole MDMW-1 described in Sections 4.2.1 and 4.2.2 of this report. Table 5.1 summarizes the depth, geologic formation and hydraulic conductivity of the layers used in the cylindrical model. Hydraulic conductivities in the model are assumed to be isotropic.

The cylindrical model employed 14 layers (Table 5.1) to provide the required vertical definition and 50 horizontal grid blocks to simulate a 2.5 km distance. The horizontal grid was generated automatically by SWIFT using a logarithmic grid spacing. Consequently the grid blocks in the vicinity of the well are on the order of 10's of cm where those along the perimeter of the grid are 100's of m. A Carter-Tracy (1960) edge boundary was applied at 2.5 km. This edge boundary condition is a unique feature of the SWIFT model and accurately simulates the response of an infinite aquifer.

To simulate the behaviour of the injection period, it was necessary to select a representative set of conditions for the disposal well. These conditions were selected by averaging the properties of eight disposal wells in the same geographical area. The wells used in this averaging process included the five Esso Petroleum Canada wells and the Polymer, Sun Oil and Shell Oil wells. Weighted averages were obtained by using the total injection volumes. This approach yielded the following properties of the simulated injection well:

1.   Total Volume Injected = 5.32×10^6 bbls
8.47×10^5 m^3

Table 5.1 Cylindrical Model of Disposal Zone and Fresh
   Water Aquifer

Geologic Formation	Depth (m)	Number of Layers	Horizontal and Vertical Hydraulic Conductivity (m/s)
Fresh Water Aquifer	35-36	1	1.0×10^{-5}
Kettle Point Formation Shale	36-49	3	1.0×10^{-9}
Hamilton Group Shale and Limestone	49-147	4	1.0×10^{-9}
Dundee Formation Limestone	147-179	1	1.0×10^{-10}
Dundee Formation Limestone and Lucas Formation Dolomite - injection zone	179-243	3	2.5×10^{-7}
Lucas Formation Dolomite	243-261	1	1.0×10^{-6}
Lucas Formation Dolomite and Amhertsburg Formation Dolomitic Limestone	261-291	1	4.0×10^{-6}

2. Injection Zone Thickness = 65 m @ 190 - 255 m

(628 - 836 ft)

3. Injection Duration = 11.7 years

Using these average values and the data from borehole MDMW-1, a simulation was performed with the cylindrical model for both the injection period and a subsequent 16 year recovery period. The end of the simulation period corresponds to 1988. The simulation indicated that in order to match a typical well head pressure of 2400 kPa the hydraulic conductivity of the injection zone at 179-243 m would have to be increased from the field measured value of 2.0×10^{-8} m/s to 2.5×10^{-7} m/s. As acid treatment and hydraulic fracturing were often employed by the well operators to increase injection rates this increase in hydraulic conductivity is reasonable. The results of the simulation can be seen in the pressure profile in Figures 5.3 and 5.4. The major observation resulting from this simulation is that the pressure within both the disposal zone and overlying strata builds up and decays very rapidly.

It is recognized that some disposal wells injected greater volumes than the average value of 8.47×10^5 m^3 over the life of the disposal operations. Because the approach adopted in our modeling effort assumes the formation hydraulic properties of the injection zone are uncertain and may be adjusted to match the reported well head injection pressure, the results of the cylindrical model are not significantly affected by different injection volumes and rates.

On the basis of rapid build up and decay of pressure within the injection zone it was decided, for the purpose of estimating the flux through an abandoned borehole, that the flow could be assumed constant. This assumption is valid provided the flow through the abandoned borehole is much less than the injection flow rate. This assumption was checked for the cases examined and found to be valid. Figure 5.5 presents the potentiometric surface of the 65 m thick disposal zone for the injection well and an abandoned borehole at 100 m radial distance. It can be seen that the magnitude of the perturbation induced by the abandoned borehole is relatively small. Hence the assumption regarding steady-state conditions is valid.
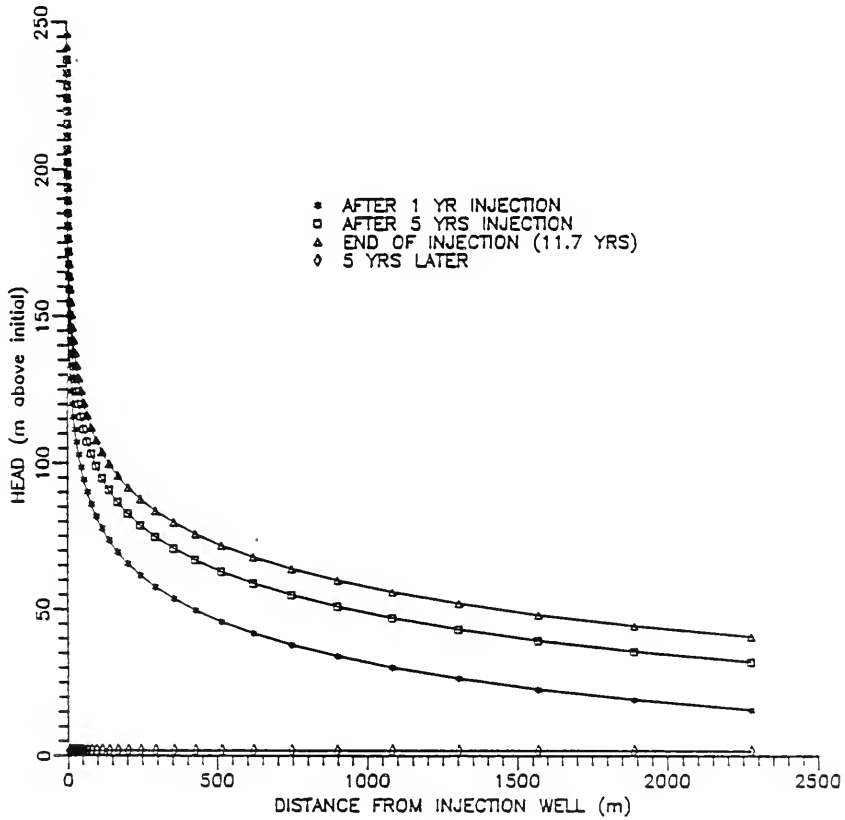
HYDRAULIC HEAD PROFILE IN INJECTION FORMATION

FIGURE 5.3
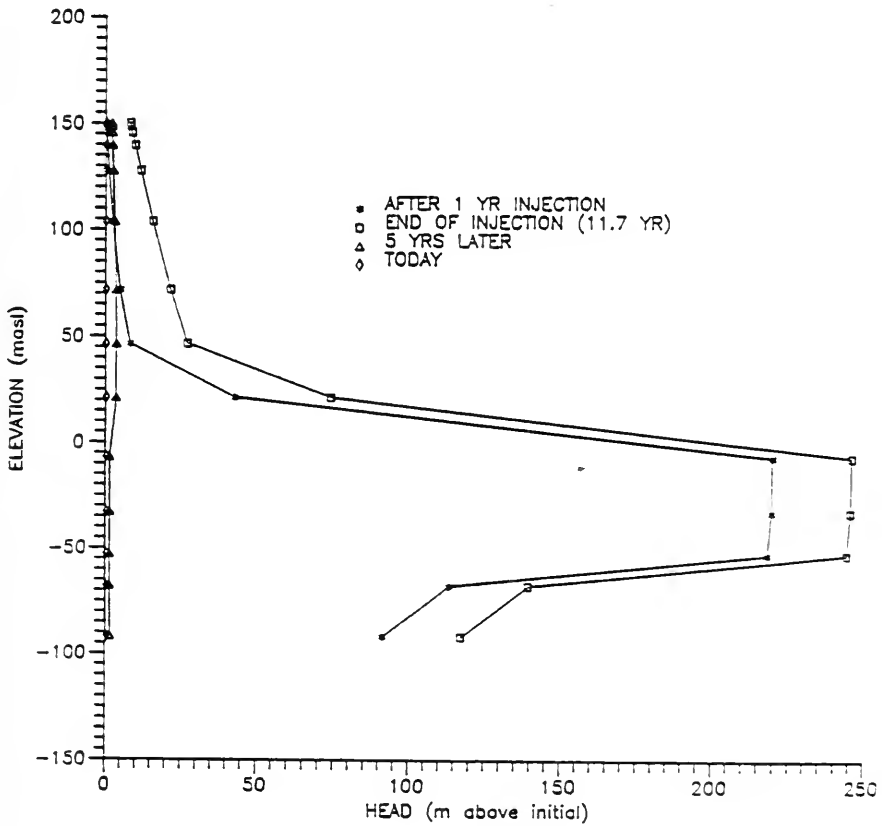
FIGURE 5.4

HYDRAULIC HEAD DISTRIBUTION IN OVERLYING STRATA ALONG INJECTION WELL AXIS
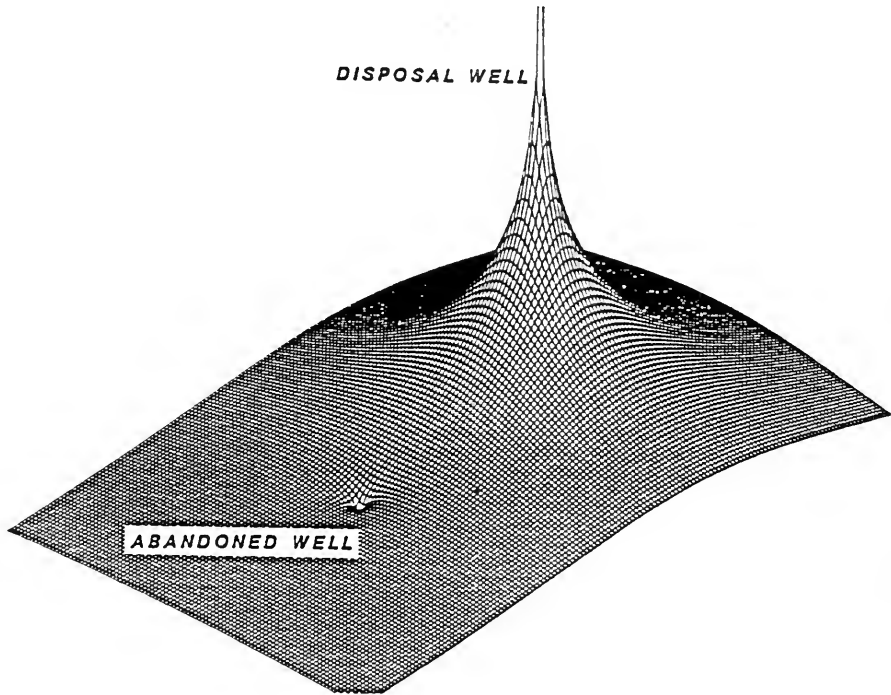
DISPOSAL WELL

ABANDONED WELL

Drawn by	Date	POTENTIOMETRIC SURFACE OF DISPOSAL
Checked by	Date	FORMATION SHOWING IMPACT OF DISPOSAL
Revisions	Date	WELL AND AN ABANDONED BOREHOLE

FIGURE 5.5

The magnitude of this constant flow rate up the abandoned borehole (over the injection period) was calculated by considering the magnitude of the head differential between the Fresh Water Aquifer and the disposal zone (at distances of 100 and 1000 m and neglecting density effects) and distributing this head difference between the disposal zone (head depression at the abandoned borehole) and the Fresh Water Aquifer (head buildup) based on the transmissivities of both intervals. The formations between the disposal zone and the Fresh Water Aquifer are assumed to be of low hydraulic conductivity and do not accept any of the fluid flux that migrates up the abandoned borehole. The magnitude of friction loss along the borehole was also examined and found to be negligible.

Although the assumption of constant flow through the borehole can be addressed relatively easily the question of the concentration of this flow is more difficult to resolve. To evaluate this factor, the following approach was adopted:

1. Assume undispersed plug flow in the disposal zone;

2. Using information on injection flow rates (Q_i), abandoned borehole flow rate (Q_a) and disposal zone properties of porosity (n) and thickness (h), calculate the time dependent radial position (r) of the cylindrical fronts associated with the injection and abandoned boreholes:

$$r_i = \sqrt{Q_i t / \pi h n}$$

$$r_a = \sqrt{Q_a t / \pi h n}$$

where: subscripts i and a refer to injection and abandoned wells and t is time since injection started.

3.   Following the method of Bear (1979, p. 290) the concentration of flow through the abandoned borehole at any point in time is determined from the ratio of the arc length defined by the overlapping cylindrical fronts to the total arc length or circumference of the cylindrical front of the abandoned borehole. The concentration history of the flow up an abandoned borehole is then determined by performing the above calculations at each time step.

Using this approach and a porosity of 10%, concentrations were calculated for three active zone thicknesses (1, 10 and 65 m) and two distances (100 and 1000 m) for the abandoned borehole. At a distance of 1000 m an active zone of 1 m was necessary to allow waste to reach the abandoned borehole. For the other two thicknesses no waste reached the borehole. At a distance of 100 m waste reached the borehole for all active zone thicknesses considered. Concentration of waste flowing through the borehole can be seen for all cases in which the waste reached the borehole in Figures 5.6 and 5.7. For the best estimate of disposal zone thickness of 10 m, and open borehole at 100 m, the waste reaches the Fresh Water Aquifer within 0.25 years and is at disposal well concentrations within 1.3 years.

5.2.3   Fresh Water Aquifer Transport Model

The previous modeling was undertaken to obtain a flux to use as a contaminant loading to the Fresh Water Aquifer. The loading estimates were then used as input to transport simulations of the Fresh Water Aquifer to determine the spreading of potential contaminant plumes within the Aquifer.

The transport model of the Fresh Water Aquifer was constructed using a radial grid or mesh comprising some 400 grid blocks over a radial distance of about 600 m. A radial grid was selected because the dominant flow direction within the Fresh Water Aquifer in response to flow up an abandoned borehole is radial. It can be shown that the radial hydraulic gradients within the Fresh Water Aquifer in response to flow up an abandoned borehole are several orders of magnitude greater than the existing natural hydraulic gradients. The steady
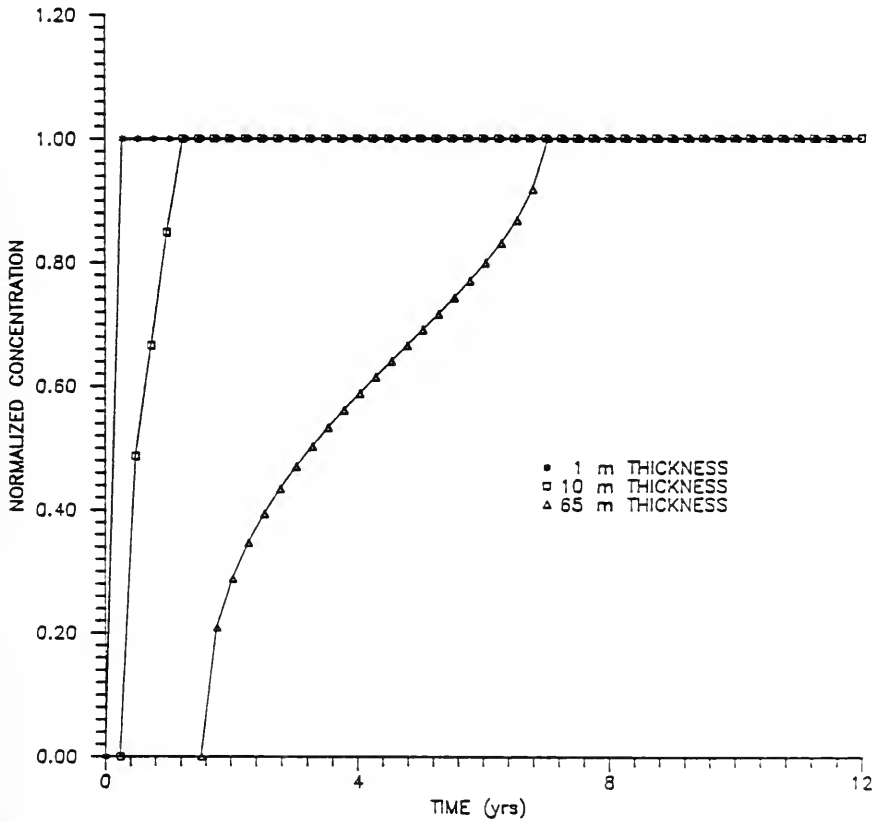
CONCENTRATION OF FLUX THROUGH AN
ABANDONED BOREHOLE AT 100 M
(C=1.0   INJECTION CONCENTRATION)

FIGURE 5.6
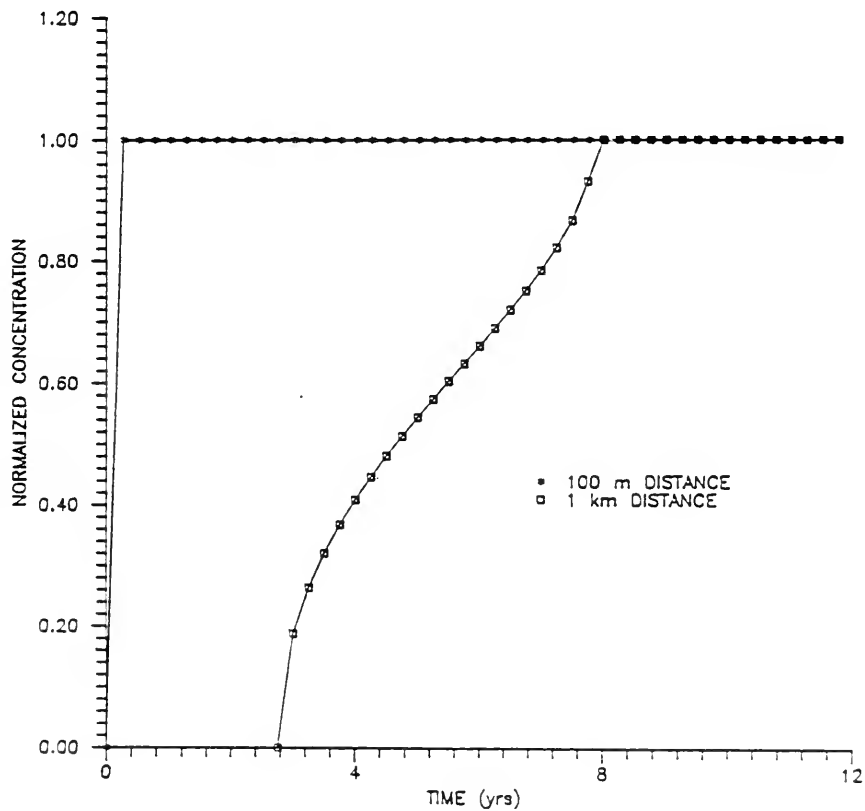
CONCENTRATION OF FLUX THROUGH AN ABANDONED BOREHOLE FOR ACTIVE ZONE THICKNESS OF 1 M
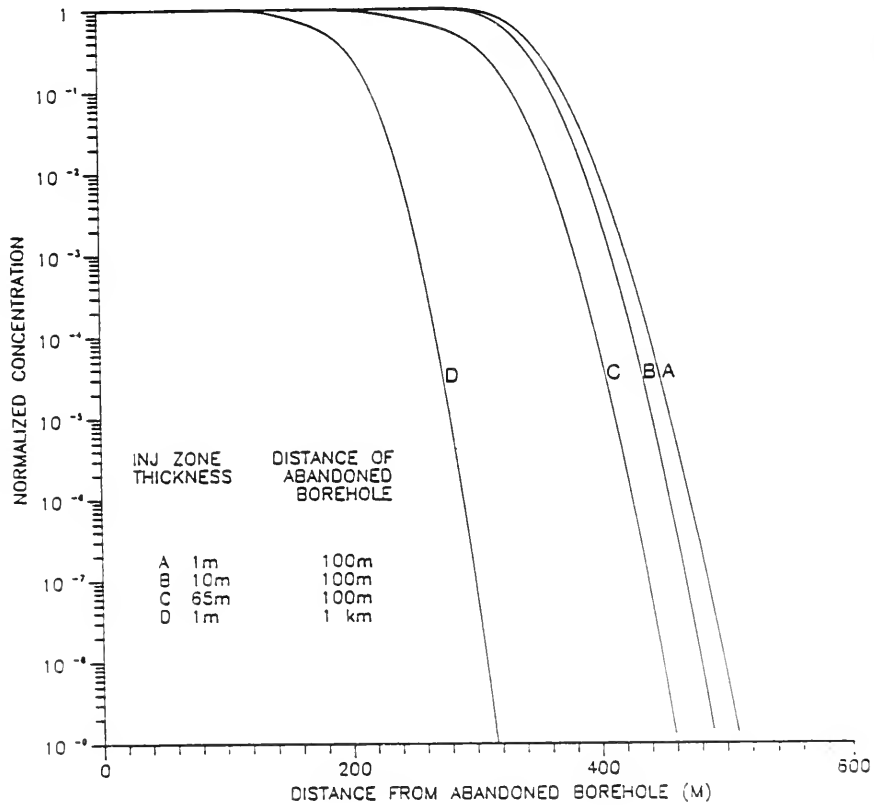
FIGURE 5.7

radial flow field around the abandoned borehole in the Fresh Water Aquifer was simulated using an Aquifer transmissivity of $1 \times 10^{-5} \text{ m}^2/\text{s}$, Carter-Tracy boundary conditions at the outside edge of the 600 m grid blocks to simulate infinite aquifer conditions and a hydraulic head buildup at the abandoned borehole as the inner boundary condition. This head buildup and associated flow rate to the Fresh Water Aquifer was assumed to instantaneously reach steady conditions and varied with the spacing of the abandoned borehole.

Transport within the radial flow field established in the Fresh Water Aquifer was simulated using the flux concentration histories shown in Figure 5.6 and 5.7 as an input boundary condition at the abandoned borehole in the Fresh Water Aquifer.

Longitudinal dispersivities of 1 m were used during all transport simulations. The selected dispersivity is considered representative of the full-aquifer dispersivities in the Fresh Water Aquifer based on data reported by Anderson (1979), Pickens and Grisak (1981) and Killey and Moltyaner (1988) for granular aquifers. For measurement scales of 5 - 500 m, these authors reported longitudinal dispersivities of 0.01 to 15 m from controlled field tests and existing contaminant plume information.

The results of the transport simulations to the end of the injection period are shown in Figures 5.8. The results shown in Figures 5.8 are also representative of the potential current (1988) plume sizes because the injection pressures in the disposal formation and in the Fresh Water Aquifer rapidly dissipate after injection and the natural gradients within the Fresh Water Aquifer are so low that the plumes would only be transported on the order of 15 m in the period after cessation of injection.

Assuming an injection concentration at the disposal well of 100,000 ug/L phenol and a reliable detection limit of phenol at 10 ug/L Figure 5.8 can be used to estimate the approximate size of phenol plume that might exist and be detected in the Fresh Water Aquifer. With the above phenol concentrations a 1×10^{-4} normalized concentration is calculated as a detection limit (i.e., 10/100,000). With this detection limit and the current best estimates of disposal zone thickness

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WASTE CONCENTRATION PROFILE IN
FRESH WATER AQUIFER AT END OF
INJECTION PERIOD

FIGURE 5.8

of 10 m, Figure 5.8 shows that a phenol plume of about 425 m radius might exist and be detected in the Fresh Water Aquifer if an abandoned borehole was located at 100 m distance. If the abandoned borehole was closer or farther away the plume size would be larger or smaller respectively. If the disposal zone was 1 m in thickness and the borehole was at 100 m, the detectable plume would only be marginally larger at about 450 m radius. If the disposal zone was 1 m thickness and the abandoned borehole was at 1 km the detectable plume would be smaller at 270 m radius. If the abandoned borehole was located at 1 km and the active injection zone was 10 m or greater in thickness, the contamination would not reach the Fresh Water Aquifer.

Some additional transport calculations were performed to evaluate the size of brine plumes due to abandoned boreholes. For these simulations the disposal zone was assumed equal to 10 m, abandoned borehole distances of 100 m and 1000 m were assumed and density differences were ignored. This latter assumption, while approximate, is conservative from the standpoint of predicting maximum plume sizes. It was also assumed, for simplicity, that only brine flowed through the abandoned borehole for the entire injection period. The results of these simulations are presented in Figure 5.9 and illustrate the maximum Fresh Water Aquifer brine plume sizes would be of the same order of magnitude as those of injected waste (Figure 5.8). For example, for a detection limit of 1,000 mg/L chloride and assuming the chloride content in the disposal zone at 100,000 mg/L, a normalized detection level of 1×10^{-2} is determined. With an abandoned borehole at 100 m, and an disposal zone thickness of 10 m the detectable plume size would be about 400 m radius. For an abandoned borehole at 1 km radius the detectable plume radius would be about 300 m.
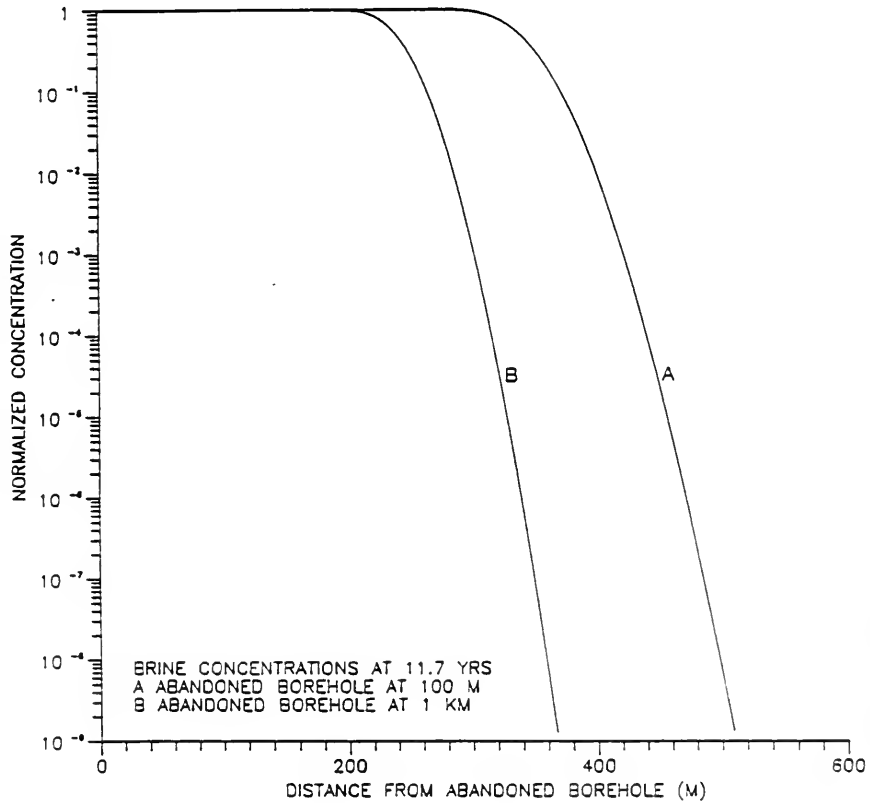
BRINE CONCENTRATION PROFILE IN
THE FRESH WATER AQUIFER AT END
OF INJECTION PERIOD

FIGURE 5.9

6.   EXTENT, POTENTIAL MIGRATION AND IMPACT OF CONTAMINATION

This section describes the extent, potential migration and impact of
contamination in the Fresh Water Aquifer and deep geologic formations in the
Sarnia study area.   Contamination may result from displaced formation waters
(brines) and industrial wastes (phenolic waters) that result in elevated
concentrations of chemical constituents above background levels.   Indicators of
contamination are chloride for displaced formation waters and phenol for injected
industrial wastes.

6.1   FRESH WATER AQUIFER

Groundwater sampling completed in this study (30 monitoring wells) and
earlier by MOE (1985) (21 domestic wells), GLAL/Esso (1987) (10 monitoring wells)
and Hatch-Golder (1985) (20 tunnel piezometers) provide a sampling network of
81 points within or close to the Fresh Water Aquifer in Sarnia and Moore
Townships, Lambton County.   A sampling network of 53 points exists within the
area of investigation defined in the current study (Figures 1.1 and 3.1).

Using phenol as an indicator of industrial waste in the Fresh Water
Aquifer, recently measured, elevated levels of phenol (>10-20 ug/L) were only
detected in EPC wells RW-1 (11,000 ug/L), AQ1 (10,900 ug/L) and AQ11 (200 ug/L)
and in CN tunnel piezometers 24+10 P2 (150 ug/L), 24+10 G4 (120 ug/L) and 24+70
P1 (520 ug/L).   No significant levels of phenol were detected in the MOE and EC
monitoring and domestic well network.   The detected phenols occur within an 800
m by 600 m area located at the north end of EPC property in the vicinity of the
CN tunnel, the St. Clair River, EPC disposal well DW-3 and some former flowing
wells.   The contamination is localized in this 800 m by 600 m area as EPC
monitoring wells AQ2 and AQ3 located within the area do not show significant
phenol concentrations.

The phenol contamination detected in EPC wells AQ1 and RW-1 is located
on the western limb of the bedrock valley adjacent to the St. Clair River.   EPC
well AQ11 is within the centre of the bedrock valley.   Because of uncertain

groundwater flow directions in the bedrock valley, the migration direction of this contamination is uncertain. It is likely that some of this contamination migrates to the St. Clair River and some may be directed downward to the deeper geologic formations in the bedrock valley or laterally to the groundwater sink created by the CN tunnel. As a worst case it can be assumed that all of the groundwater flow per unit Aquifer width into the bedrock valley (i.e., 0.57 m^3/a) discharges to the St. Clair River. Assuming the width of the contaminated zone is 300 m, and the contaminant concentration is 10,000 ug/L a phenol loading of 4.7 g/d would discharge to the River.

Cleanup of this contaminated zone on EPC property by groundwater pumping is potentially dangerous and may introduce more contamination to the Fresh Water Aquifer.
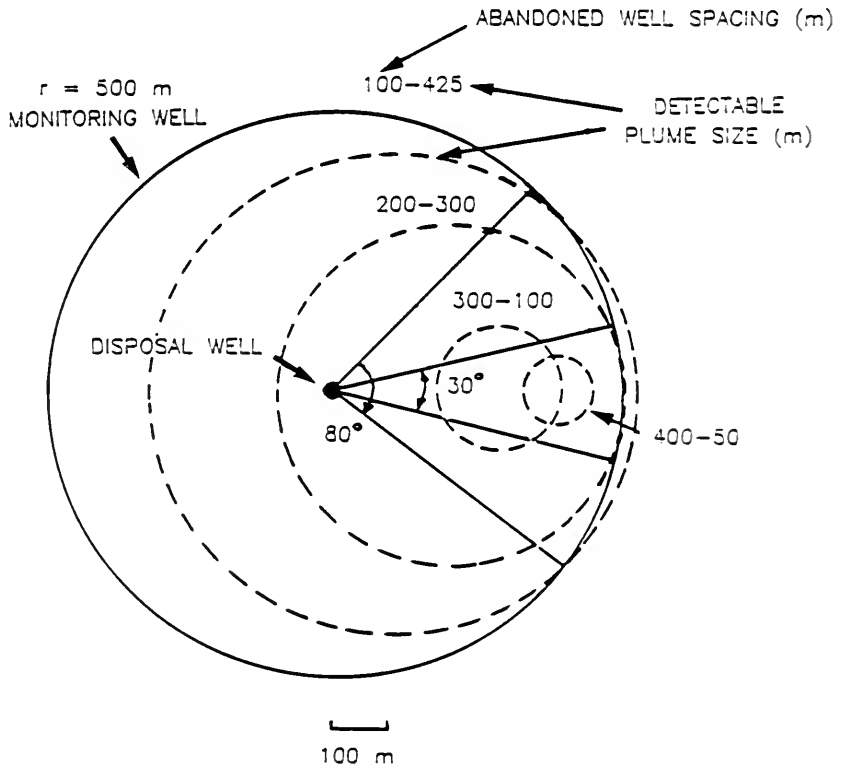
Phenol detected in the CN tunnel piezometers is likely indicative of contamination of the Fresh Water Aquifer. The majority of this contamination flows toward the tunnel, is collected within the tunnel as seepage and is pumped to the River. A small amount of the contamination likely flows directly to the River through the alluvial deposits. Based on the phenol concentration of seepage water measured in the tunnel sump (28 ug/L) and an average pumping rate of 18 m^3/d the estimated loading to the St. Clair River from pumped seepage is at 0.5 g/d. The total phenol loading to the St. Clair River from measured phenol concentrations at the sampling points is about 5.2 g/d. As the average flow in the St. Clair River is 5100 m^3/s, mixing would rapidly reduce this phenol concentration to below detection limits.

Chloride data shows elevated (>1000 mg/L) concentrations in EPC wells RW1 (7170 mg/L), AQ1 (6000 mg/L), CN tunnel piezometers 24+10 P2 (6000 mg/L), 24+10 G4 (6000 mg/L), 24+10 P1 (1300 mg/L), and MOE wells 6-85 (1670 mg/L) and 2-87 (1240 mg/L). With the exception of the data from wells 6-85 and 2-87 these elevated chloride data are in the same areas of elevated phenols. Following the approach described for estimating phenol loading, the chloride loading to the St. Clair River from the Fresh Water Aquifer assuming chloride concentrations of 6000 mg/L is calculated at 2.8 kg/d in the area of RW1 and AQ1. The chloride

loading to the St. Clair River from the CN tunnel is calculated at 47.7 kg/d based on reported chloride concentrations in the tunnel sump of 2650 mg/L and an estimated pumping rate of 18 m^3/d. Total chloride loading to the St. Clair River from measured sources is therefore about 50 kg/d which when mixed with the 5100 m^3/s flow of St. Clair River water would result in a 0.11 ug/L increase in chloride content in the River.

The above loading calculations are based on measured water quality parameters in monitoring wells. Because of the large size of the study area it is not possible or practical to provide complete monitoring well coverage of the study area and an estimate of the probability of detecting contaminant plumes and the likely size and impact of undetected contaminant plumes in the Fresh Water Aquifer is required.

A rudimentary estimate of the probability of detecting contaminant plumes in the Fresh Water Aquifer due to fluid migration up an abandoned borehole can be made utilizing the results of the modeling study described in Sections 5.2.2 and 5.2.3. Figure 5.8 and Section 5.2.3 show that the contaminant plumes within the Fresh Water Aquifer due to industrial waste migration up an abandoned borehole located at 100 m radius from the disposal well would be detectable at a radius of about 425 m. The probability of a single monitoring well located at a radial distance of 500 m from the disposal well detecting this 425 m radius plume can be determined from the percentage overlap of the loci of points defining the monitoring well radius and the detectable plume size. This approach is illustrated in Figure 6.1 for the conditions described above. The monitoring well circle at radius 500 m has overlap with the plume size of 425 m over 80° of arc of the locus of possible monitoring well points. Therefore the probability of detecting this 425 m plume is 80/360 or 0.22. Figure 6.1 also shows the minimum detectable plume size for an abandoned borehole at radii of 200, 300 and 400 m extrapolated from the modeling results. The probability of detecting a contaminant plume resulting from flow up an abandoned borehole located at 200 m radial distance from the disposal well is 30/360 or 0.08. For the conditions described in Section 5.2.2 and 5.2.3 the waste from the disposal horizon only migrates to a radial distance 512 m.

GRAPHICAL METHOD FOR DETERMINING
PROBABILITY OF DETECTING PLUMES IN
FRESH WATER AQUIFER

FIGURE 6.1

Following the above method a probability plot of detecting contaminant plumes was constructed with abandoned well spacing and monitoring well spacing as functional parameters. This plot is shown in Figure 6.2 and is based on the modeling results and assumptions described in Sections 5.2.2 and 5.2.3 and Figures 5.8 and 5.9. The plot was generated considering industrial waste and brine waste migration to the Fresh Water Aquifer.

Figure 6.2 shows that there is negligible probability of detecting industrial waste plumes in the Fresh Water Aquifer due to abandoned boreholes with monitoring wells located at 1000 m from the disposal well and low probability for detecting brine waste plumes but only if the abandoned well spacing is between 700 and 1200 m radial distance. Brine plumes are detectable at this distance because the brine formation fluids are displaced rapidly after the start of injection by radial migration of the pressure front due to injection. Figure 6.2 also shows that with monitoring wells located at 500 m, the probability of detection is increased slightly for industrial waste plumes but only if the abandoned borehole is located at less than 100 m from the disposal well. Increased probability of detection of brine plumes is also observed for a wider range of abandoned borehole spacings with a monitoring well at 500 m radius. Figure 6.2 demonstrates that only if the monitoring wells are located at 100 m radial distance and abandoned wells are present at less than 200 m from the disposal well can a high probability of detecting industrial waste plumes be assumed. For brine plumes a high probability of detection is extended to abandoned wells located within 300 m of the disposal well.

From Figure 6.2 and the location of monitoring wells and disposal wells (Figure 3.2) it is possible to assess the uncertainty in detection of contaminant plumes due to abandoned boreholes at different locations in this study area.

In the area of EPC disposal wells, monitoring wells of the Fresh Water Aquifer are located within 100 - 300 m of the disposal wells. For these distances Figure 6.2 suggests there is about a 0.50 probability that industrial waste plumes would be detected if abandoned boreholes were within 200 m of the disposal well. These waste plumes if present would be about 300 - 425 m radius.
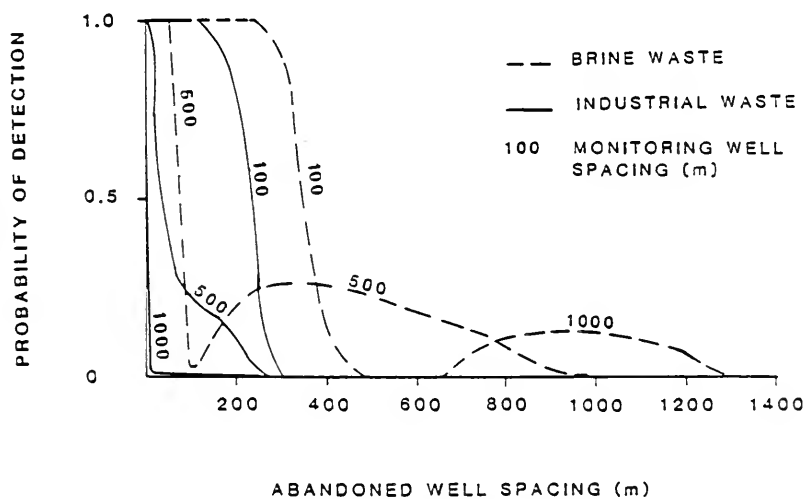
PROBABILITY OF PLUME DETECTION AS A FUNCTION OF ABANDONED WELL AND MONITORING WELL SPACING

FIGURE 6.2

However, because the EPC disposal wells are located in proximity to each other, well interference effects are likely to occur and the 0.50 probability cited above is likely underestimated.

In the area of the Polymer disposal well there is one monitoring well at about 350 m and one well at 500 m radial distance. If an abandoned well is located between 100 and 500 m distance from the disposal well, the probability of industrial waste plume detection in the Fresh Water Aquifer is less than 0.50.

In the area of the Sun Oil disposal well there is one monitoring well at a distance of about 400 m. The probability of detection of industrial waste plumes in this area if an abandoned borehole existed is low (less than 0.25).

The area of Shell Canada disposal wells has two monitoring wells at distances of 800 and 900 m. Given these distances there is a very low probability of detecting industrial waste plumes and only a low probability (less than 0.25) of detecting brine plumes if abandoned boreholes existed in the area.

It is significant that of all the monitoring and disposal well areas, only the area of EPC disposal wells, according to the above model, has a greater than 0.5 probability of detecting an industrial waste plume in the Fresh Water Aquifer. The only industrial waste plume detected by monitoring wells in the Fresh Water Aquifer was on EPC property.

The above discussion assumes that abandoned boreholes exist in the vicinity of each disposal well. This is unlikely to be the case but it is not possible to reliably know. As a worst case scenario it can be assumed that an undetected contaminant plume of about 200 m radius and concentration of 10,000 ug/L phenol exists in the vicinity of the Polymer, Sun Oil and Shell Canada disposal wells and the area of the EPC disposal wells DW4 and DW5. These disposal wells are all close to the St. Clair River so that loading to the St. Clair River is of the concern. The loading to the St. Clair River from each of these four undetected plumes would approximate 6.2 g/d or a total of 25 g/d.

These estimates may be high as they neglect fluid losses to deeper geologic formations in the bedrock valley and assume a contaminated Aquifer cross section of 400 m. The potential phenol loading to the St. Clair River calculated at 25 g/d may result in phenol concentrations near the point of discharge near the river bottom that are above detection limits (of 1 ug/L). Subsequent mixing in the St. Clair River would reduce the concentrations to an increase of .057 ng/L which is much less than the detection limit for phenol.

The potential phenol loading to the St. Clair River from undetected plumes is small in comparison to industrial/municipal point source loadings identified by the Upper Great Lakes Connecting Channels Study (1988). These point source phenol loadings range from 0.9 - 4.3 kg/day.

6.2   DEEP GEOLOGIC FORMATIONS

Because high chloride concentration saline waters and brines exist through the deep geologic formations in the Sarnia area, contamination in this discussion includes only industrial wastes which are typically characterized by high phenol contents.

Based on phenol contents, industrial waste at concentrations of 30,000 - 40,000 ug/L phenol occurs in the Lucas dolomite over a relatively narrow 11 m interval from 185.7 - 196.6 m depth. Using tritium as an indication of drill water contamination, the concentration of phenol at this interval may be as high as 50,000 ug/L.

The distribution of phenol below the zone of residual contamination centred at 192 m indicates that there has been very little migration of industrial waste downward to deeper sections of the Lucas Formation and the Amherstburg Formation. The phenol concentration from GC/MS analyses reduces from 40,000 ug/L at 192 m to 206 ug/L at 207 m depth to less than 10 ug/L below 220 m depth. The distribution of hydraulic conductivity and the current hydraulic head profile will continue to prevent vertical migration of the waste downward through the pore space of these formations to the deeper sections of the Detroit River Group.

Some vertical migration of industrial waste upward into the Dundee Formation was evident in this study. However the fact that the upper sections of the Dundee Formation are oil bearing reduces the permeability of the formation to waste water and the vertical migration was limited to about 10 m. Upper sections of the Dundee contain phenol levels of 1000 - 4000 ug/L that apparently occur naturally in association with the crude oil. Overlying the Dundee Formation and acting as a natural barrier to vertical migration, are the lower shale sections of the Hamilton Group known as the Bell and Arkona Formations. The combined thickness of these low permeability clay shales is 57 m. It is unlikely that any significant vertical migration of industrial waste through the pore space of these shales occurred during the period of waste injection. The low permeability of these shales and the Dundee limestone as well as the current hydraulic head profile will continue to prevent vertical migration of waste upward through the pore space of these formations.

The hydraulic head within the zone of residual contamination is apparently stable over the seven month monitoring period of this study and considering density effects is equal to a water level of 168.39 m AMSL. This is about 14-15 m below the fluid level in the Fresh Water Aquifer in the same location and about 8 m below the level of the St. Clair River in the Sarnia area. Flow between the zone of residual contamination and the Fresh Water Aquifer/St. Clair River that may have occurred during the waste injection period is now, based on the measured levels, from the Fresh Water Aquifer/St. Clair River to the zone of residual contamination. This flow direction now acts to mitigate the potential contaminant plumes introduced to the Fresh Water Aquifer due to abandoned boreholes by having the displaced brine and/or waste water within the Fresh Water Aquifer now flow to the disposal zone.

Although the results of this study show that there has been little to no vertical migration of industrial waste through the pore space of the formations, the results from sampling suggest that there has been considerable lateral migration within the disposal horizon. The extent, migration rate and direction of this lateral flow both during injection and especially today is unknown. The occurrences of breakouts and flowing wells (described in Section

2.3) suggest the migration was extensive over distances of 1-2 kilometres and to the United States. The fate of the 8,000,000 m^3 of industrial waste injected in the Detroit River Group can only be determined by knowing the current rate and direction of fluid flow within the disposal zone of the Lucas Formation. Currently, there is insufficient data to reliably determine this.

Although the natural vertical hydraulic conductivity of the Hamilton Group is very low and this unit acts as an important barrier to vertical flow, there are several high hydraulic conductivity and laterally extensive limestone layers within the Hamilton Group that today likely contain industrial waste. One to three meter thick permeable limestone horizons were intersected at 65, 74 and 123 m depth. The zones at 65 and 123 m depth are now high pressure (likely gas) zones evident on the pressure profiles and the zones at 74 and 123 m depth were high pressure gas production zones during drilling. Industrial waste likely is present in the 74 and 123 m depth horizons based on earlier drilling observations, work reported by GLAL/Esso (1987) and the results of chemical analyses of waters collected in this study. The waste was likely introduced to these horizons via improperly cemented or completed disposal well and/or cavern well casings or abandoned boreholes. Because of the high pressures and high hydraulic conductivity of these formations there is significant potential for lateral migration of industrial waste.

The interval at 74 m depth is of particular concern as the bedrock valley and the Fresh Water Aquifer which extends to depths of at least 79 m in the area of DOW property intersects this limestone aquifer. Assuming the hydraulic head in the Fresh Water Aquifer in the bedrock valley is about 177 m AMSL the head measurement in borehole MDMW-1 (188.15 m AMSL) indicates the flow in the horizon has a gradient of about 0.01 toward the bedrock valley. With a formation thickness of 2 m and a hydraulic conductivity of 1×10^{-5} m/s the flow rate per unit width through this horizon toward the bedrock valley is 2×10^{-7} m^3/s or 6.3 m^3/a. This flow rate is 12.6 times greater than the flow rate through the Fresh Water Aquifer.

There is considerable uncertainty in the level and extent of contamination within the 74 m depth limestone unit and therefore the loading estimates to the Fresh Water Aquifer in the bedrock valley. However the fact that this horizon was pressurized with industrial waste in 1967 and 1969 and that the only two monitoring wells completed to the horizon (the AQ11 well (GLAL/Esso, 1987) and the MDMW-1 well of this study) intersected waste at concentrations of 6,000 - 12,000 ug/L, suggest the levels and extent of industrial waste contamination are significant.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1   CONCLUSIONS

Based upon the work described in this report and in consideration of the study objectives outlined in Section 1.2 we conclude the following for the Fresh Water Aquifer and deep geologic formations.

7.1.1   Fresh Water Aquifer

- The Fresh Water Aquifer is a thin (2 m average thickness) discontinuous sand and gravel and fractured shale aquifer that generally follows the bedrock surface with average hydraulic conductivity of 5×10^{-6} m/s.

- A buried bedrock valley of depth 60 - 80 m below ground surface subparallels the St. Clair River and is located about 500 to 1000 m east of the current channel. The bottom of the bedrock valley is about 30-40 m below the surrounding bedrock. Lower sections of the bedrock valley are infilled with reworked till and alluvial deposits and the Fresh Water Aquifer within the bedrock valley is permeable with an average hydraulic conductivity of 1×10^{-4} m/s.

- The Fresh Water Aquifer is generally confined by 30-70 m of low hydraulic conductivity (10^{-10} m/s) clay till. Below the St. Clair River the clay till thins in places to as little as three meters and more permeable alluvial deposits are present.

- Groundwater flow within the Fresh Water Aquifer is northwesterly across the study area and generally discharges to the St. Clair River. Flow on the U.S. side of the River is a mirror image to that on the Canadian side. Groundwater fluxes toward the bedrock

valley on the Canadian side average 0.57 m^3/a per unit Aquifer width. Hydraulic heads measured in monitoring wells completed within or proximate to the bedrock valley indicate that some of the flow entering the bedrock valley discharges to depth, likely to deeper geologic formations.

• Monitoring well studies show that industrial waste and brine contamination of the Fresh Water Aquifer is limited to an 800 m x 600 m area generally on Esso Petroleum Canada property and below the St. Clair River, in the vicinity of the CN tunnel, EPC wells RW-1, AQ1 and AQ11 and EPC disposal well DW3. Neglecting flow losses to depth to the bedrock valley, the phenol loading to the St. Clair River from this contamination is estimated at 5.2 g/d which given the flow rate within the River would be rapidly reduced to below detection levels. Similar calculations for chloride indicate a chloride loading to the St. Clair River from measured sources of about 50 kg/d.

• Assuming some undetected phenol contaminate plumes may exist within the Fresh Water Aquifer in the vicinity of the St. Clair River and existing disposal wells due to fluid flow up an abandoned borehole, a worst case loading estimate to the St. Clair River can also be determined. This potential loading is calculated at 25 g/d which with mixing in the River would result in an increase in phenol concentration of .057 ng/L which is much less than the detection limit for phenol at 1 ug/L. This potential phenol loading is small in comparison to identified municipal/industrial point sources.

• Additional loading of industrial and brine waste to the Fresh Water Aquifer within the bedrock valley is possible through discharge of contaminated formation waters located at 74 m depth within the Widder Formation of the Hamilton Group.

7.1.2   Deep Geologic Formations

- Groundwater within the deep geologic formations is typically Na-Cl type saline waters or brines with density of 1.03 to 1.13 and increased salinity with depth. The density and total dissolved solids content increases dramatically below a depth of about 220 m in the Lucas Formation.

- Industrial waste characterized by phenol (30,000 -40,000 ug/L), benzene, toluene, xylenes, ethyl- and methyl-benzenes (200 - 5800 ug/L) and naphthalenes and methylnaphthalenes (50 - 829 ug/L) is restricted to a narrow 11 m interval between 185.7 and 196.6 m depth within the upper section of the Lucas Formation dolomite. Vertical migration of this waste both upward and downward through the pore space of the overlying and underlying formations has been restricted to about 10 m.

- Current hydraulic conductivity and hydraulic head conditions provide hydraulic isolation of the zone of residual contamination centred at 192 m and restrict vertical flow from this zone. The hydraulic head within the zone of residual contamination is stable at an equivalent water level of 168.39 m AMSL. Considering density effects this level is about 14-15 m below the fluid level in the Fresh Water Aquifer at the same location and about 8 m below the level of the St. Clair River in the Sarnia area. Therefore the current potential fluid flow directions are from the Fresh Water Aquifer and the St. Clair River toward the zone of residual contamination in the Lucas Formation.

- The chemical composition of the industrial waste from the Lucas Formation dolomite does not contain chlorinated volatile organics such as perchloroethylene and carbon tetrachloride and therefore is dissimilar to the St. Clair River "blobs" detected in 1985. This chemical dissimilarity and the current hydraulic head

conditions indicates that the occurrence of the St. Clair River "blobs" were not related to upward movement of industrial waste from the Detroit River Group to the St. Clair River.

- Lateral flow within the disposal zone is likely significant and the fate of the 8,000,000 m^3 of waste disposed to the Detroit River Group can only be determined by understanding the current flow rates and directions within the disposal zone. There is insufficient data to reliably determine this.

- High permeability limestone layers of 2-3 m thickness at 74 and 123 m depth in the Hamilton Group in the Sarnia area likely contain industrial waste with phenol concentrations of 6000 - 12,000 ug/L. Hydraulic heads in these zones are above the level of the head in the Fresh Water Aquifer. The zone at 74 m depth is exposed within the deeper sections of the bedrock valley and flow is likely from the formation to the Fresh Water Aquifer in the bedrock valley. The level and extent of contamination within this horizon is not well known. The industrial waste was likely introduced to these horizons through improperly completed disposal wells, cavern wells or abandoned wells.

7.2   RECOMMENDATIONS

Based on the results and conclusions described in this study we recommend the following activities to more clearly define the hydrogeology of the Fresh Water Aquifer and deep geologic formations.

- Monitoring of water levels in the MOE and EC monitoring well network on a semi-annual basis.

- Water quality sampling of all monitoring wells in the MOE and EC monitoring well network on a semi-annual basis.

- Analyses of water samples for indicator parameters of contamination such as phenols and major ion chemistry.

- Sampling of monitoring wells in the MOE and EC monitoring well network for environmental isotopes ^{18}O, ^2H, and ^3H. Several of the earlier samples contain drill water contamination.

- Pressure monitoring of borehole MDMW-1 on a semi-annual basis to determine the long term formation pressures in the deep borehole. Many intervals within the Hamilton Group have yet to reach equilibrium pressure conditions.

- Water quality sampling of the sampled intervals in borehole MDMW-1 on a semi-annual basis. Analyses of water samples for phenols, major ion chemistry, volatile organics and acid extractable organics. Stable and reproducible water quality analyses have not yet been collected from the majority of intervals within the borehole.

- The potential for contamination of the Fresh Water Aquifer from industrial waste contamination in the 74 m and 123 m depth limestone layers in the Hamilton Group should be investigated. This potential is greatest from the 74 m depth horizon which likely flows into the Fresh Water Aquifer in the deeper sections of the bedrock valley. Drilling, testing, casing installation and monitoring of four new boreholes to the Hamilton Group are recommended. Two boreholes should be drilled within or proximate to the bedrock valley and two boreholes should be drilled east of the bedrock valley.

- To understand the fate of the industrial waste disposed to the Detroit River Group, two deep boreholes completed to the disposal formation are required to quantify the current directions and rates of groundwater movement.

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